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Tubular Space Truss Structure For SKITTER II Robot

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ABSTRACT

The "tubular truss" model of Skitter II is a proof of principal design. The model will replicate the operational capabilities of Skitter II including its ability to self-right itself.

The project's focus was on the use of light weight tubular members in the final structural design. A strong design for the body was required as it will undergo the most intense loading. Triangular geometry was used extensively in the body, providing the required structural integrity and eliminating the need for cumbersome shear panels. Both the basic femur and tibia designs also relied on the strong geometry of the triangle. An intense literature search aided in the development of the most suitable weld techniques, joints, linkages, and materials required for a durable design. The hinge design features the use of spherical rod end bearings. In order to obtain a greater range of mobility in the tibia, a four- bar linkage was designed which attaches both to the femur and the tibia. All component designs, specifically the body, femur, and the tibia were optimized using the software package IDEAS 3.8A Supertab, developed by Structural Dynamics Research Corporation. The package provided essential deformation and stress analysis information on each component's design. The IDEAS software was used on Apollo DN 560 computer manufactured by the Apollo Corporation.

The final structure incurred only a 0.0544 inch deflection in a maximum (worst case) loading situation. The highest stress experienced by any AL6061-T6 tubular member was 1920 psi . The structural integrity of the final design facilitated the use of Aluminum 6061-T6 tubing.

The Tubular Truss Structure of Skitter II is an effective and highly durable design. All facets of the design are structurally sound and cost effective.

PROBLEM STATEMENT

Background

A tubular space truss is needed for the framework of SKITTER II. This frame is lighter, more mobile, and stronger than the existing model. A versatile structure is required to accomodate different tasks such as a drilling base or a crane foundation. The Skitter II model is powered by fewer actuators and can support itself in more positions than its predecessor. Additionally, the SKITTER II can work in hazardous environments without affecting its structural integrity.

Performance Objectives

The tubular truss SKITTER II has high degree of mobility using truss members that do not appreciably deform under conditions of high stress and torsion. The strutcture employs few moving parts in order to obtain a high degree of reliability while requiring little maintenance. The SKITTER II walks on all types of terrains and inclines and be able to right itself in the event of inversion.

Constraints

SKITTER II is designed for maximum manuverability while utilizing as few movable parts as possible. The design should have a high strength to weight ratio in both structural configuration and material selection. In order to achieve a high degree of mobility, a range of motion for the femur-body and femur tibia joints is specified at greater than 180 º and less than 180 º respectively. The overall length of the femur and tibia is 30 inches each. Tubular members are the beam geometry.

DESCRIPTION

Introduction

The SKITTER II is a three legged transport vehicle designed to demonstrate the principle of a tripod walker in a multitude of environments. The design is based on few moving parts and a simple mechanical system. The motivation behind these systems is that a few moving parts and a simple mechanical system will increase reliability and decrease maintenance.

The design calls for an efficient structure which consists of as few members as possible. The main goals behind the design of the Skitter II is to improve the strength, mobility, flexibility, reliability, and the range of motion while keeping the total weight to a minimum.

The structural design consists of four major parts; the central body and the legs. The legs are connected to the central body in 120 º intervals. Each leg is made up of two parts; a femur and a tibia. The relative motion between the femur and tibia is controled by electromechanical actuators. 1 inch and 3/4 inch tubular aluminum members are utilized throughout the entire structure.

Body

The body is composed of two equilateral three sided pyramids connected at there bases. The top of the pyramids are truncated to form the minimum triangular inner space that is required to secure the various implements. The body is shown in Figure 1.

Femur

The femur is an all welded tubular structure which is attached to the body and the tibia. It connects to the body via spherical rod ends which allow it to rotate 100 º relative to the body. The overall length of the femur is 30 inches. The femur is shown in Figure 2.

Tibia

The tibia is an all welded tubular structure which attaches to the end of the femur with spherical rod ends and has a range of motion of plus or minus 90 º relative to the femur. The tibia is shown in Figure 3.

Driving Components

Each leg is powered by two linear actuators that transmit 1500 lbs. of force. The body is connected directly to the femur by the actuator while the femur-tibia connection is made through an amplifier linkage.

STRUCTURAL ANALYSIS

Introduction to Analysis

SKITTER II's body and 3 femurs and 3 tibias were designed to perform effectively under conditions of high stress and loading. A worst case loading scenario was employed when optimizing all three component designs on Structural Dynamics Research Corporation's Ideas 3.8a Supertab. The situation in which SKITTER II endures its most intense loading and highest stresses occur when the legs are extended horizontally away from the body . A vertical load of 150 lbs. is applied at each foot while adjust to insure minimal or no rotation about the knee and hip. The members experience high stresses and deflections in this position. Using the Supertab software, a simulation of the worst case loading was performed. Members were added to the original structural designs to eleviate high stress and reduce deflection. One inch tubing was employed in critical areas and 3/4 inch tubing was used in less critical members.

The limits of optimization were governed by the material properties of 6061-T6 aluminum which was used throughout the structure. Because Aluminum 6061-T6 has a decreased yield strength upon welding (Sy = 40,000 psi - reduced to 0 - 8,000 psi), the structure was ultimately desiged so that the maximum stress in any member did not exceed 8,000 psi. The joints and welding configurations were designed with this reduced yield strength.

It is important to note that the final structure is capable of withstanding stress and loads well above those encountered in the worst case scenario. Because the designs are structurally stable, a wide range of materials including composites can be used without compromising the structural integrity.

Body

The main body of SKITTER II utilizes the triangle for it's main geometry. Two 12 inch equalateral triangles, 10 inches apart, form the top and bottom surfaces of the body. A 24 inch equalateral triangle forms the midplane between the two smaller triangles. Viewing the body from the top (Figure1c) the orientations of all three triangles becomes visible.

Two different tubing sizes were used in the body to obtain optimal performance. The 24 inch equalateral triangle is made of three one-inch nominal diameter aluminum 6061 tubes. The larger diameter tubing was used at the hinges to the legs to insure both a continuous fit at the hip and a strong, durable connection. All other tubing, including the 12 tubes which connect the top and bottom triangles to the middle triangles, are sized at 0.75 inch nominal diameter.

As describe in the analysis section and Appendix 1C, the body experiences at most a 960.75 lb input at each point of the top triangle in the worst case situation. These three forces result from the 3 body actuators adjusting to the applied loads at each tibia. Despite the loading conditions, the body's maximum deflection is only 0.0067 inches. The maximum deflection occurs at the top of each of the 6 connecting tubes located on the top half of the body. These 6 tubes also assume the most stress; maximum principle stress in the worst case situation is 1940.0 psi (Appendix1C).

The body consists of 21 aluminum (6061) tubes all connected by welds. The total weight of the body, using a density of 0.098 lb/in3, is approximately 4.5 lb not including the weight of the welds. Of all three structures (body, femur, and tibia), the body is the most stable and structurally sound. Little deflection is seen even with loading beyond the worst case scenario.

Femur

The femur is 30 inches long, 19 inches wide at the hip, and 10 inches wide at the knee (Figure 2). The femur consists of four 1 inch diameter tubes and thirteen 3/4 inch diameter tubes. The tubes are constructed of aluminum 6061T6 with 0.065 inch walls. Each joint is welded either in cluster form, direct welding of tubes to one another, or by gusset welds (Figure 8). There are a total of eight unique welds. The basic geometry of the structure consists of triangles and tetrahedrons to achieve lateral and vertical stability. The femur weighs five pounds.

The maximum loading condition was applied to the femur in order to size the members and to determine optimum geometry (Appendix 1B, femur loading). The maximum displacement occurs at the center point at the end at the knee; this deflection is 0.065 inches. The maximum stress occurs at the point of loading from the body-femur actuator and is 1520 psi.

The femur is connected to the body by a hip joint employing spherical rod end bearings and is connected to the tibia at the knee joint by a by a similar arrangement (Figure 6).

The two actuators that power SKITTER's movement are located on the femur. The actuator that creates relative motion between the femur and the body is attached directly to the two structures with the base being attached to the femur 17 inches from the center line of the hip joint on the center tube support. The actuator providing power for movement of the tibia is located at the crest of the structure's tetrahedron shape. This arrangement is shown below.

Refer to the Linkage section for more detail.

Tibia

Each tibia of the SKITTER II consists of three different sizes of aluminum tubing. Because the tibia takes the initial load in the worst case situation (Appendix 1A), the stresses which arise along it's members are the highest in the whole model. Therefore, the necessity arose to vary tube diameters from 3/4 inch at the hinge connection to the femur (knee) and 1 inch members along the top and at the point of actuator attachment, to 3/8 inch rod members in areas of highest stress. The decision to use rods along with tubes was made not only because it made the tibia more structurally sound, but also because it accomadated the welding requirements of the structure. The combination of aluminum tubing and rod sizes provided the necessary stability to handle the harsh stresses observed in the worst case scenario (Appendix 1A).

During worst case loading, the maximum deflection observed in the tibia is 0.0710 inches and the maximum stress is 2710 psi which is the highest stress in the structure. Both maximum deflection and stress occur at the top and surrounding support members where the force is applied.

Relative motion between the tibia and femur is obtained through the use of an actuator and a four-bar linkage. The point at which the four-bar linkage attaches to the tibia is also a critical area of stress, but not as severe as that found at the point of load application. One inch diameter support tubes were attached at the point of linkage attachment to the tibia. These thick tubes are directly welded to the top triangular frame of the tibia (Figure 9). Due to the increased area, the one inch tubes reduce the stresses which might arise as the actuator changes position.

Each of the 3 tibias of the SKITTER II consists of 11 aluminum tubes, all connnected by welds (Al6061). The total weight of the tibia is 2.5 lbs not including the additional weight of the welds. The design of the tibia was the most critical design of the three components, as the tibia endured the greatest stresses. By optimizing the structural integrity of the tibia, the performance of the femur and body is assured.

WELDED JOINTS

The frame connections of the entire structure are of welded construction. The types of welds include cluster welds where tubes are directly welded to each other and gusset welds where joints are too cumbersome to cluster weld.

Because of the large diameter tubing and the acute angles employed in the design, gusset welds dominate the connections. All tubes are aluminum 6061-T6 before welding, and the joint areas reduce to 6061-0 after welding. The various weld types are shown in Drawings 7, 8, & 9.

HINGES (HIP AND KNEE JOINT)

Each joint is similiar in design so that parts may be interchangeable between the joints. The hinge action is provided by the use of two spherical rod end bearings (Fafnir Bearing No. REP5M6) at each joint. The radial loading limit of these bearings is 2920 lbs., well above the reaction forces encountered at the joints (Appendix 1D). Common components between the joints include the bearings, bearing sleeves, and tube bushings (Hinges, Figure 6.1).

At the knee joint, the spherical rod ends are mounted into the end of the femur where the tubes have been fitted with a threaded female bushing (Hinges, Figure 6.2). At the hip joint, the bearings are mounted in the main body triangle tubes, the ends of these tubes have been plugged with bar stock in order to provide a tapped hole for the male rod end (Hinges, Figure 6.3).

At each joint, a shaft is run through the 3/4 inch diameter end tube of each leg link, tubes 7 and 18 for the femur and the tibia,respectively; refer to the frame drawings 2A and 3A for their location. The shafts are 1/4 inch diameter bar stock and are fixed in the tube by the tube bushings (Hinges, Figure 6.4). The ends of the shaft are threaded for a 1/4 inch hexnut which holds the assembly together (Hinges, Figure 6.1). Alternatively, use of a wingnut and lock washer allows for easier assembly.

DRIVETRAIN

Body Drivetrain

SKITTER moves by using a crutch- type movement to walk. This movement is achieved by lifting a leg and swinging forward on the other two legs. The momentum created by pushing off the ground with the first leg carries SKITTER forward while the leg moves ahead and comes back to the ground

SKITTER II will use linear actuators to power the leg movements. The actuators have an 8 inch stroke and a dead length of 14 inches. They produce 1500 lbs. of force. A single actuator will be used at each joint. These joints are the knee and hip joints. The knee joint connects the femur and the tibia while the hip joint connects the femur to the body.

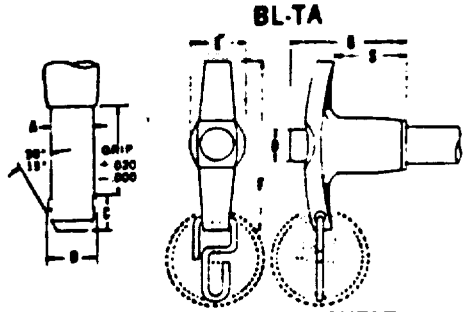
An actuator with no linkage assistance will produce relative motion between the body and the femur. At a location of 7.5 inches from the centerline of the hip joint down the centerline of the femur, the actuator was attached between the top part of the body and that point on the femur. This location provides for a range of motion of 58º above the horizontal plane and 52º below the horizontal plane (Appendix 1D).

In order to produce 180º of rotation at the knee, a four- bar linkage will be used to produce a rotational output from the linear input supplied by an actuator (Figure 1). The linear input of the actuator acts on the
crank link of the four - bar which converts the input to rotary motion at the following link (for analysis of the four - bar linkage and location, Appendix 1D). The mechanism will make use of a single actuator and the addition of a crank link and a coupler link; the ratio of the lengths of the crank link (5 inches) to the coupler link (4.67 inches) is 1.1 :1. The femur will act as the frame link and the tibia will act as the follower link of the four - bar.

Actuator Connections

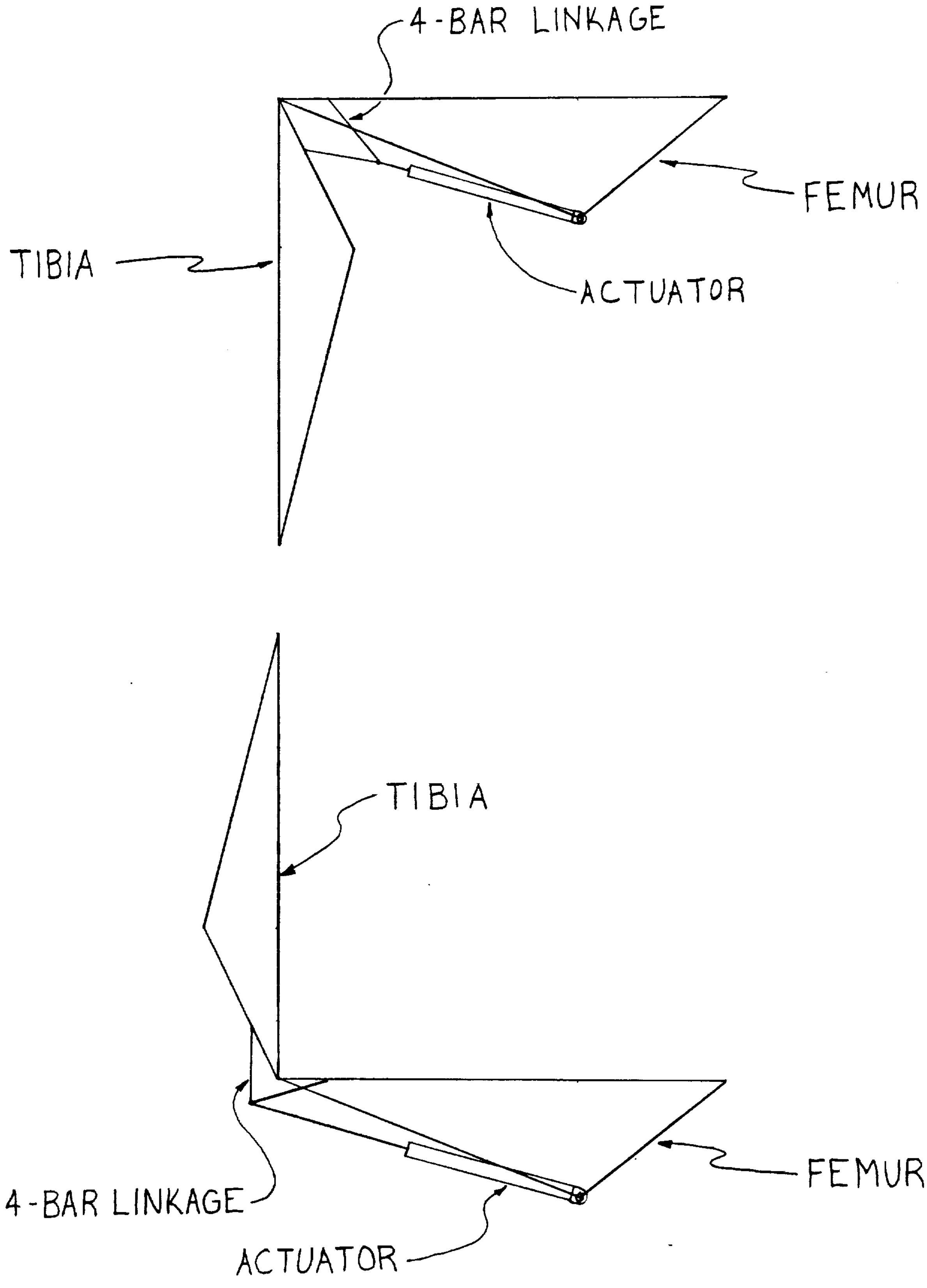
The actuator rod ends pin connect to the body and leg structures. Connection at the body makes use of a special gusset to accomodate the rod end (Figure 11). The actuator connects to the femur and the tibia along tracks which allow the actuator to be adjusted for slightly varying ranges of motion and allows for the use of different size actuators when necessary (Figure 12,13,14). The actuator rod-end connects to the track using Avibank quick-release pins no. BLC8-TA 13 S.

BL-TA



"TA" — HANDLE

NOM. DIA.	A MAX.	A MIN.	B ±.005	C +.000 −.030	D MIN.	E MIN.	F MAX.	G MAX.	H MAX.	J MIN.	K MIN.	L MAX.	M MIN.	N MIN.	P MAX.	R MIN.	S MIN.	T MIN.	CALCULATED DOUBLE SHEAR STRENGTH lbs — MIN STEEL	CALCULATED DOUBLE SHEAR STRENGTH lbs — MIN CRES.
1 2	4985	4970	594	460	435	600	2 345	1 600	1 190	1 300	720	2 360	850	1 160	1 850	1 140	885	080	32 800	36 800



TIBIA IN EXTREME POSITIONS
FIGURE 1

Material

Aluminum 6061-T6 tubing has been selected for use in SKITTER II due to its high strength to density ratio and weight effiency in designs. Other important characteristics include excellent weldability, cost and corrosion resistance. After much research and comparisons, Aluminum 6061-T6 became the obvious choice. A brief synopsis follows.

Aluminum 6061-T6, due to its high strength to density ratio, is an excellent material for structures such as trusses. Aluminum 6061-T6 also has an excellent fatique strength of cycles which will reduce down time and lower maintenance costs. Al6061-T6 also is light in weight which is very important to the design of our structure. The weakest part of the structure will be at the joints due to welding. Because of the range of temperatures experienced during welding, some physical properties will be altered. The yield strength after welding was 8 kpsi. This value of yield strength is still above the maximum stress analyzed in SKITTER II and provides a safety factor of 4 . As a note, around 1-3% of the material's properties may be regained by reheating the entire structure.

Another excellent property of the Aluminum 6061-T6 involves its corrosion resistivity. It also has good resistance to stress corrosion cracking, where there has been no known cases of failure in service.

Al6061-T6 is manufactured in the United States and is very competitive price wise.

CONCLUSION

The final design of SKITTER II satisfies many of the original performance objectives. The entire structure of the SKITTER II utilizes a high mobility although the general motion constraints were not met. The original specifications called for a range of 180º or more and less than 180º for the femur-tibia and femur-body joint respectively. The final design attained a range of 180º for the femur-tibia and 100º for the femur-body. The femur-body range was restricted due to the range limitations of the single linear actuator.

Thin walled aluminum 6061 - T6 tubes were employed in the entire structure to achieve a total structure weight of 27 lbs. The high yield strength of the aluminum 6061-T6 (40,000 lb/in^2) results in a high strength to weight ratio. The construction of each member is designed to withstand torsional forces and bending forces in addition to resisting buckling due to compression forces. Additional thought was given to the design of the welded joint since the material might might lose some of it's strength due to annealing at the welded points.

The entire structure of SKITTER II employs only six moving parts. This low number increases reliability and reduces maintanance costs. The relative motion of the parts is achieved by six actuators. Three of the actuators are located at the femur-body joint and three at the femur-tibia joint.

RECOMMENDATION

Using Aluminum 6061-T6 instead of aluminum 5083 would result in a structure that is not only more rigid, but one that has stronger connections due to the better weldability of Aluminum 6061-T6. Rotary actuators would improve the mobility of the femur and tibia while eliminating amplifying linkages. Eliminating these linkages would reduce the number of moving parts.

ACKNOWLEDGEMENTS

Many individuals have contributed to the design of SKITTER II. Special thanks goes out to our instructor Mr. James Brazell for his continued support and advice throughout the quarter. We also thank Mr. Gary McMurry and Mr. Brice MacLaren for their contributions to this project. Additional thanks goes out to the following individuals for their contributions to the design of SKITTER II:

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Dr. C. Meyers, Assistant Professor
Dr. A. Ferri, Assistant Professor
Yancy Brothers Company
Mr. J. Walker, Torrington Company

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DRAWINGS

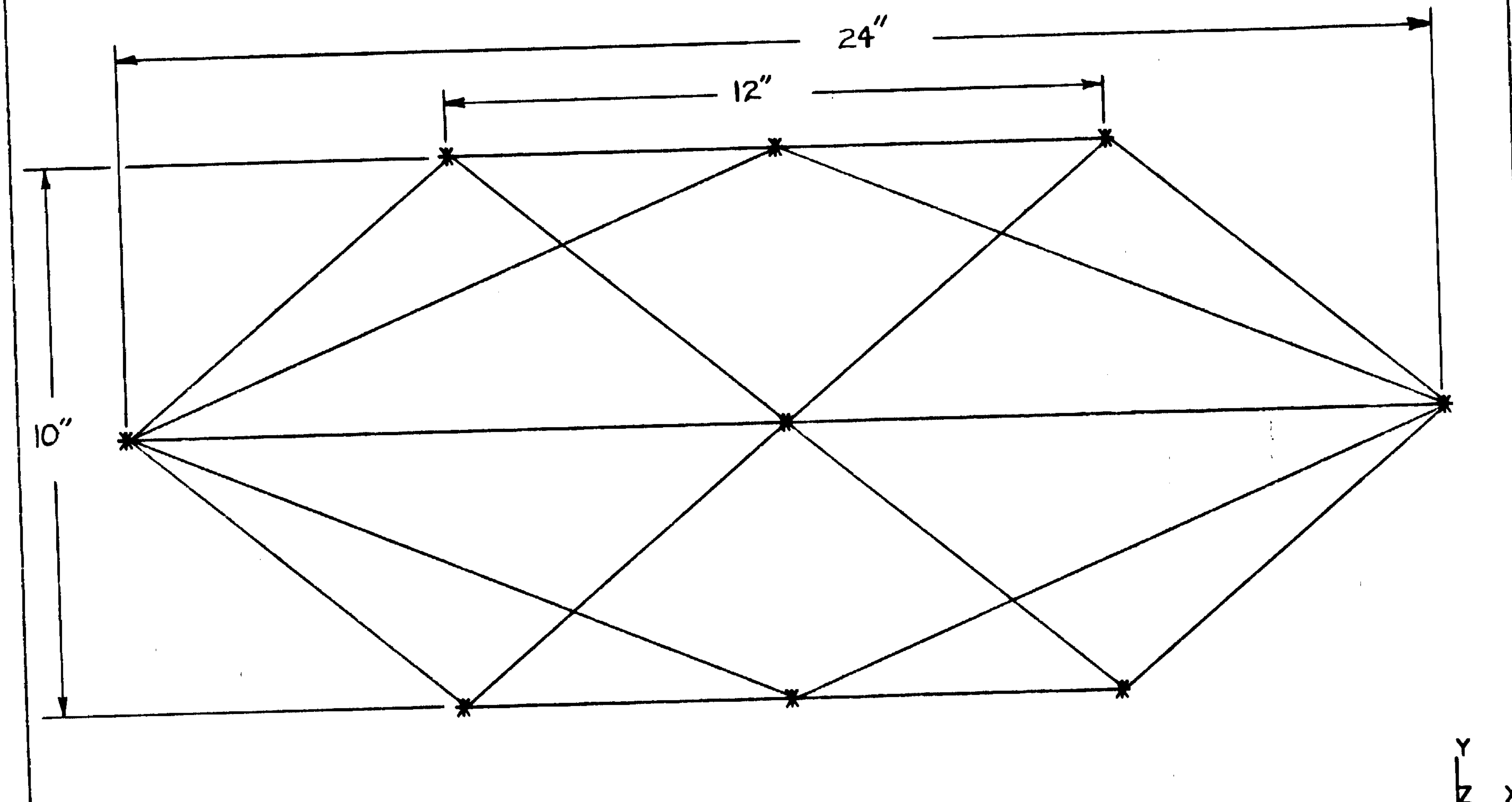
A) Skitter II Frame

B) Hinges

C) Weldments

D) Actuator Connections and Linkages

SKITTER II FRAME



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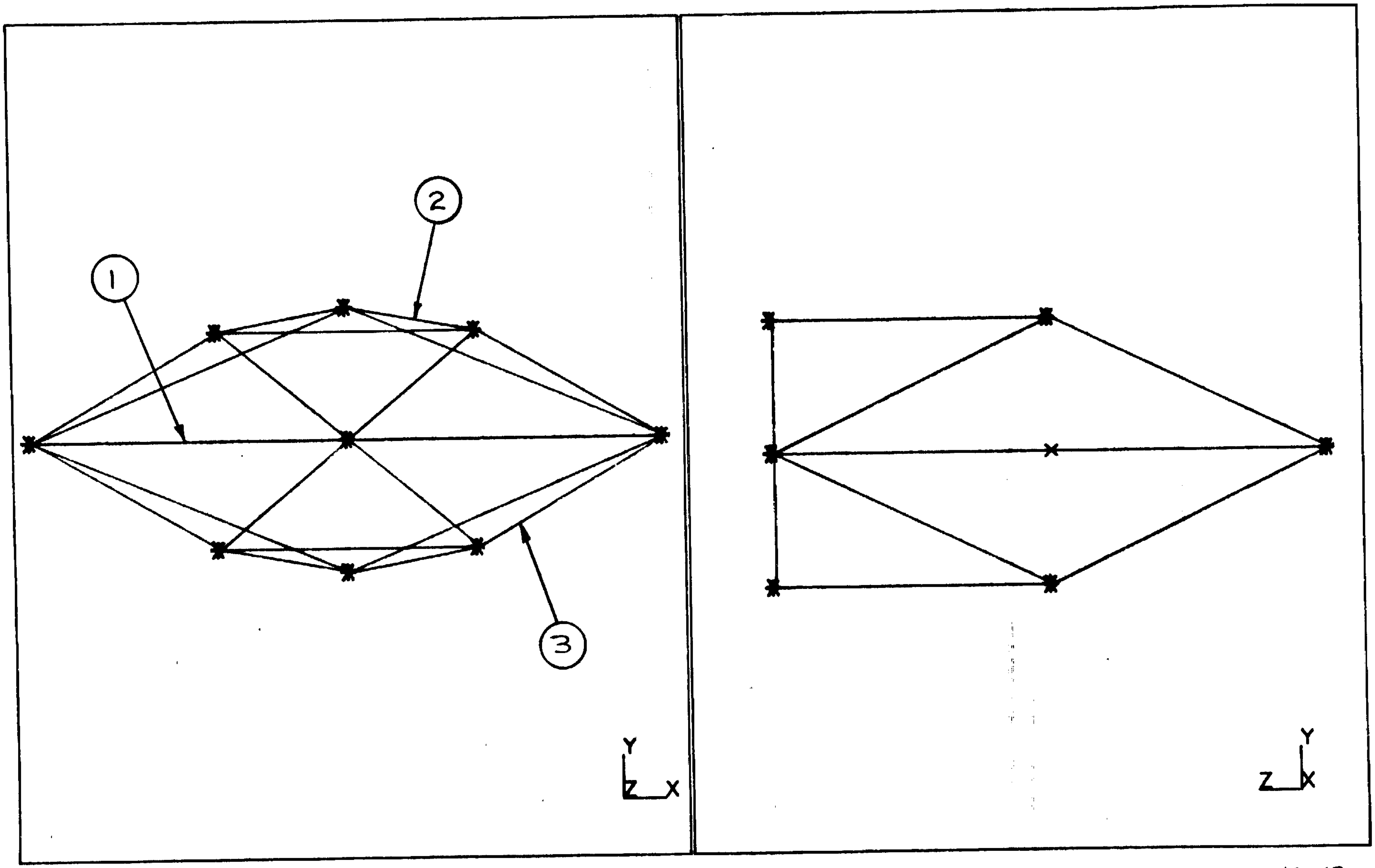
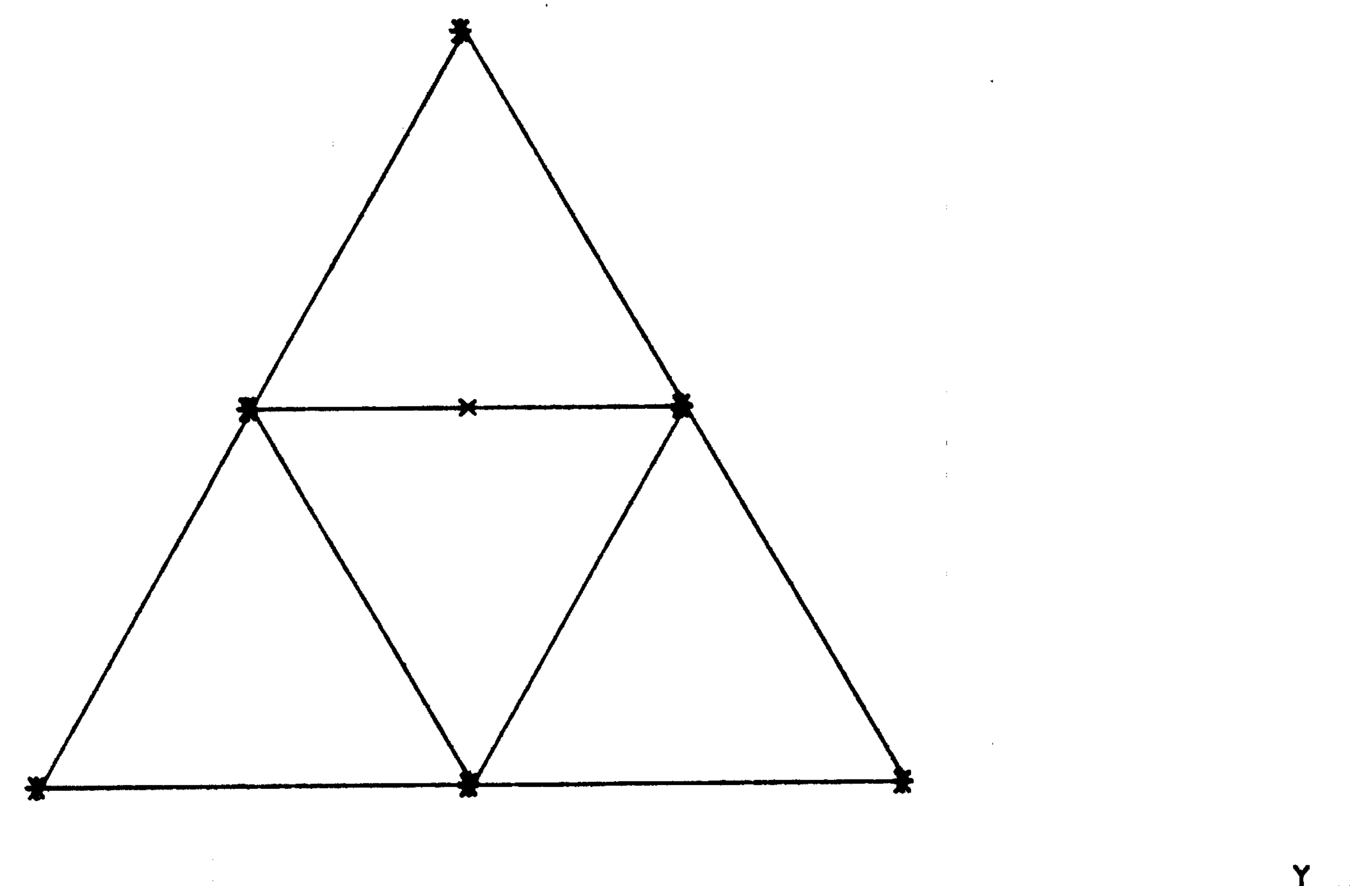


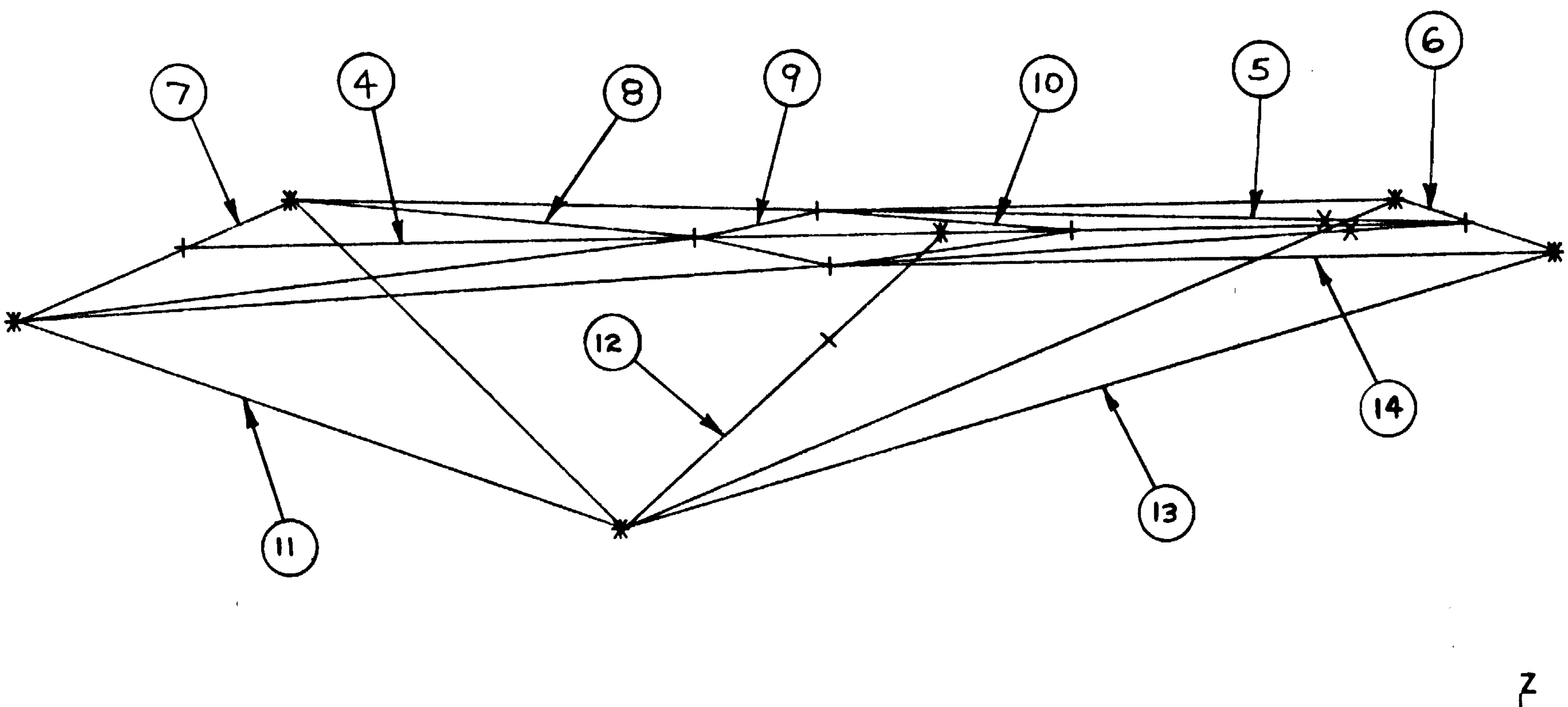
BODY

DWG. 1B



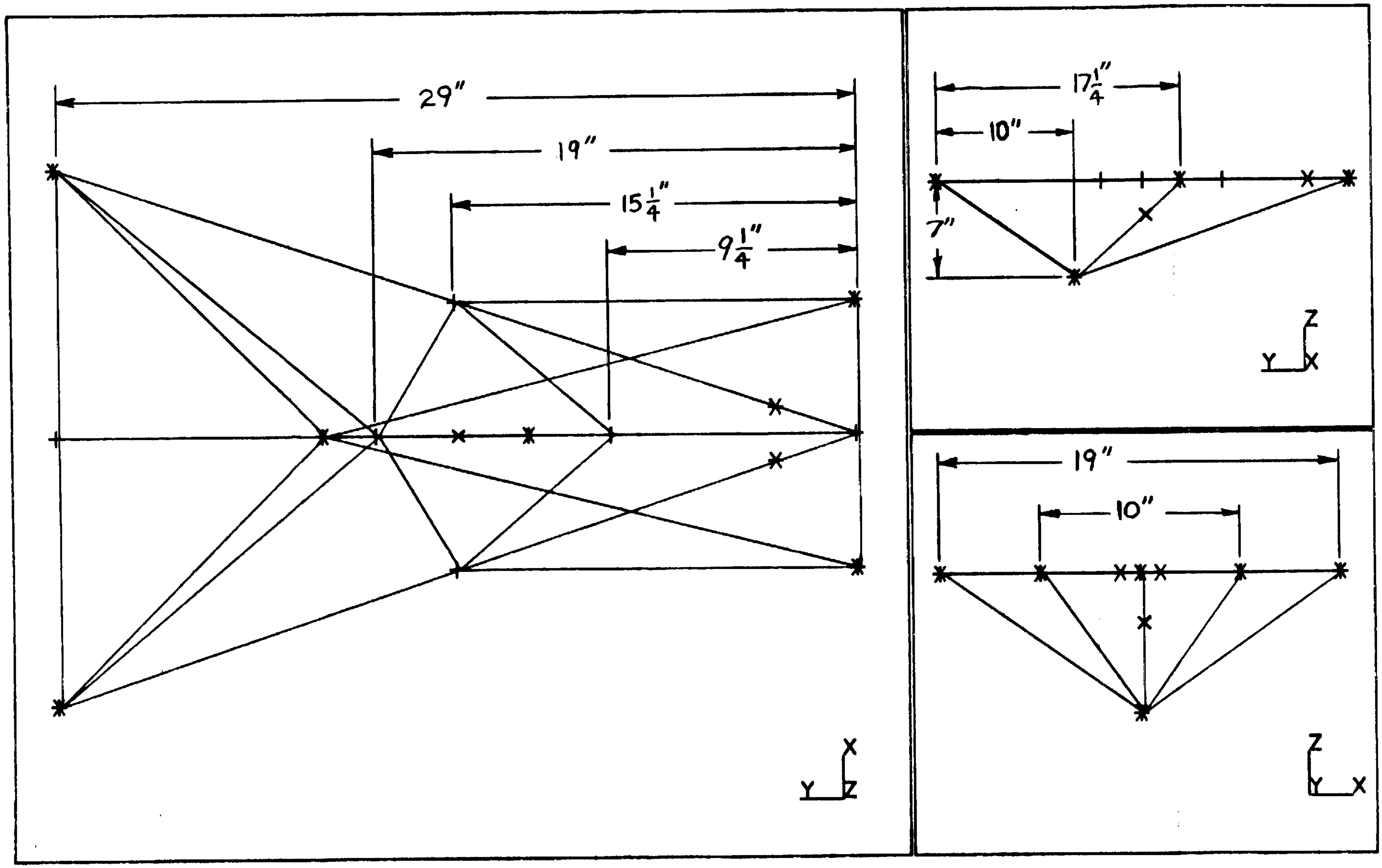
BODY

DWG. 1C



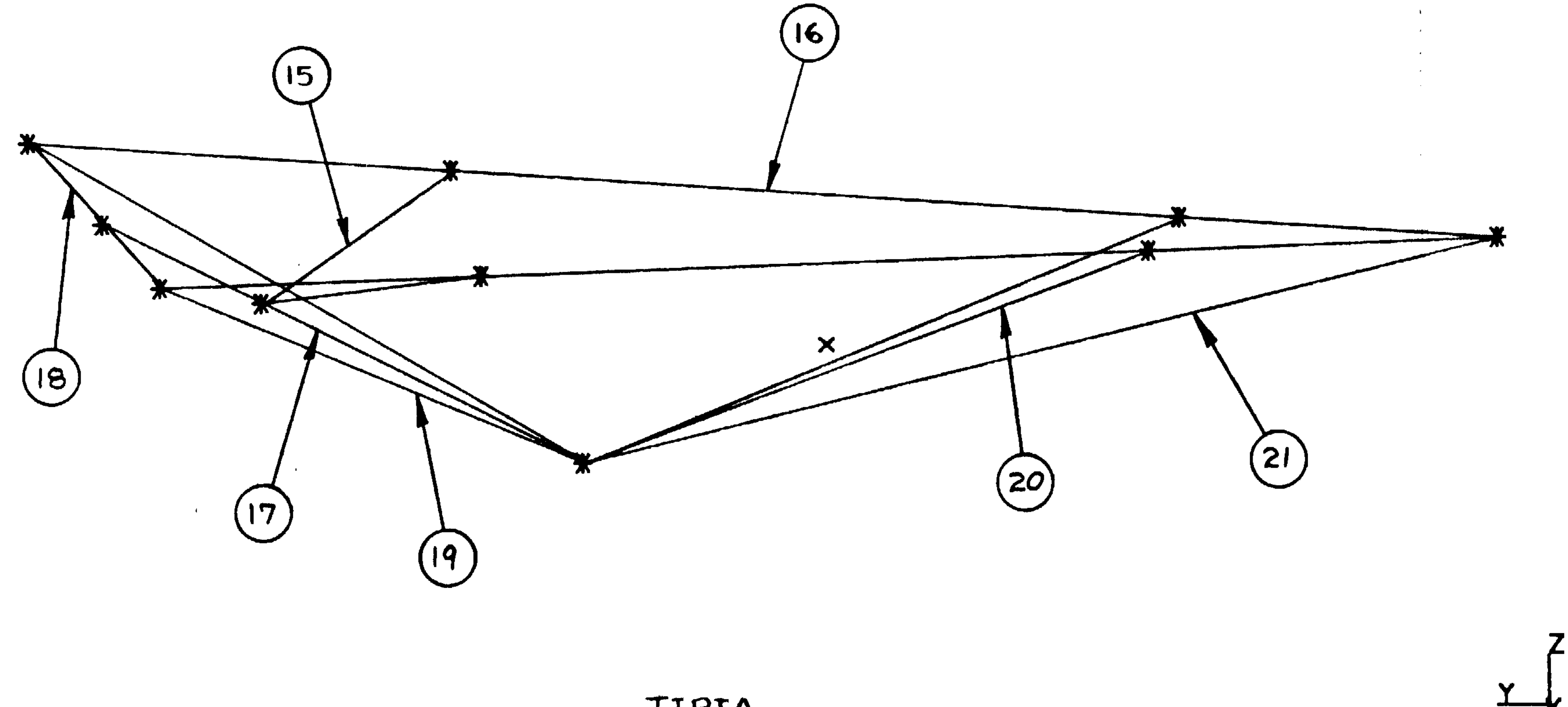
FEMUR

DWG 2A



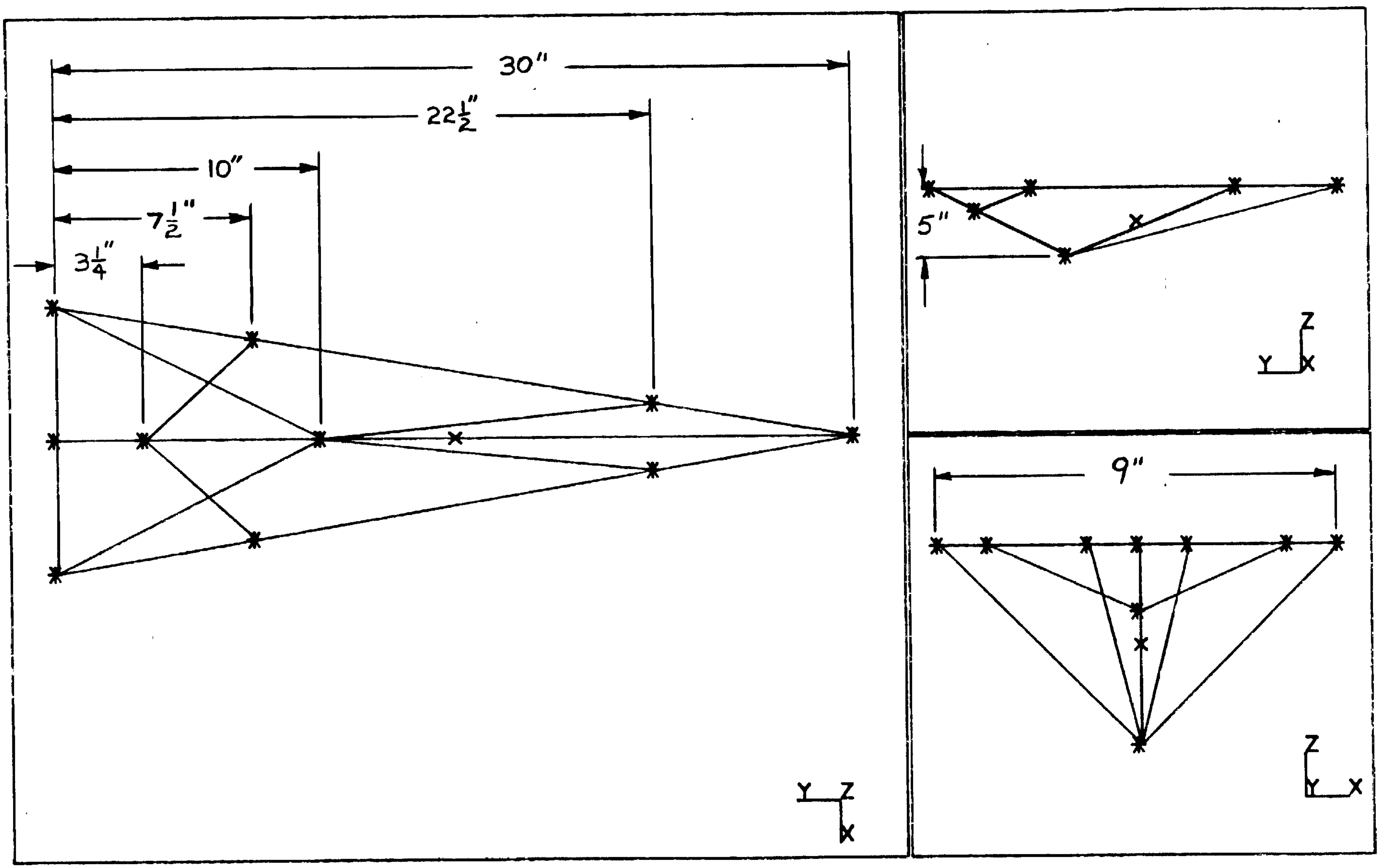
FEMUR

DWG. 2B



TIBIA

DWG. 3A



DWG. 3B

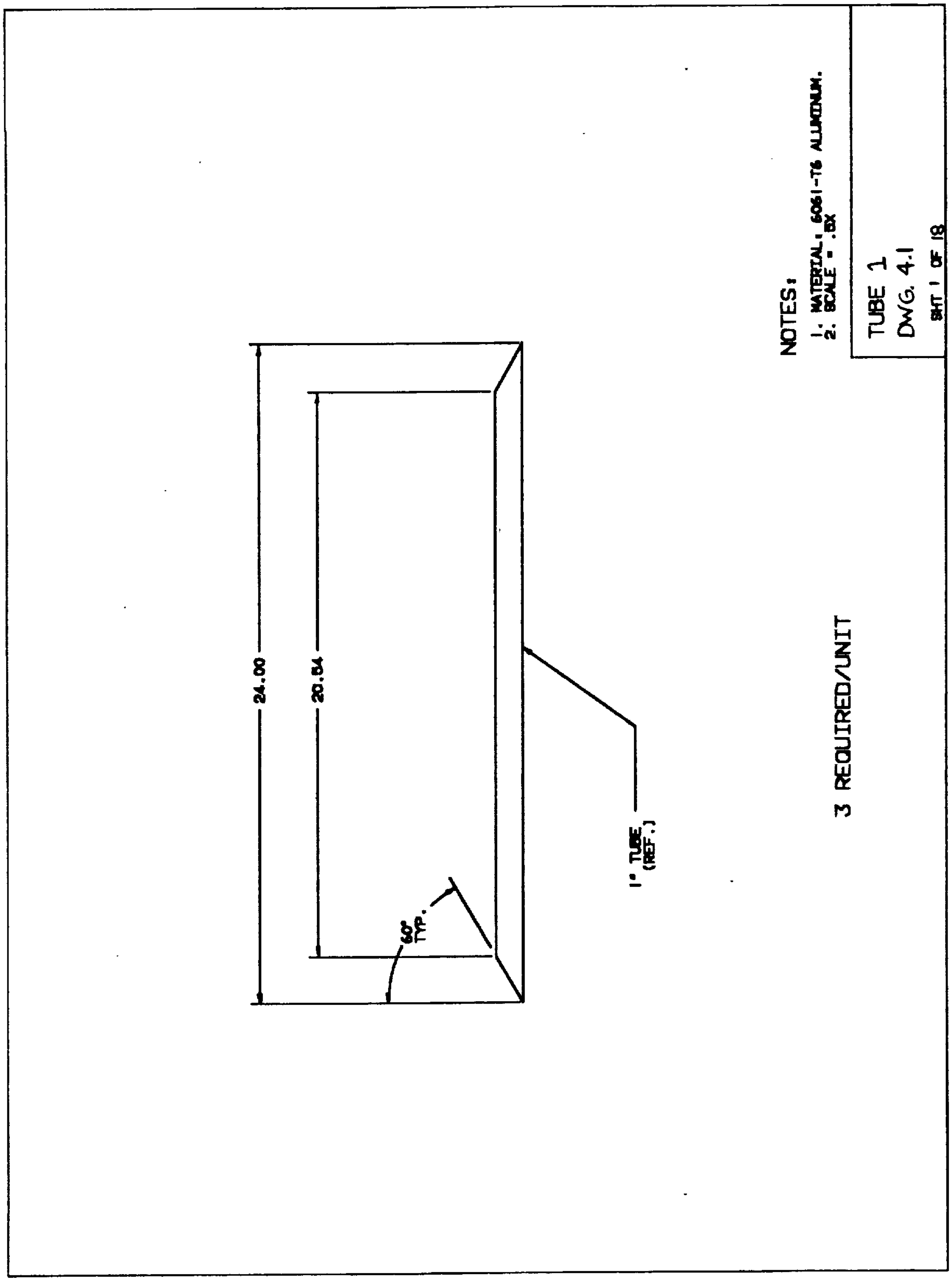
TIBIA

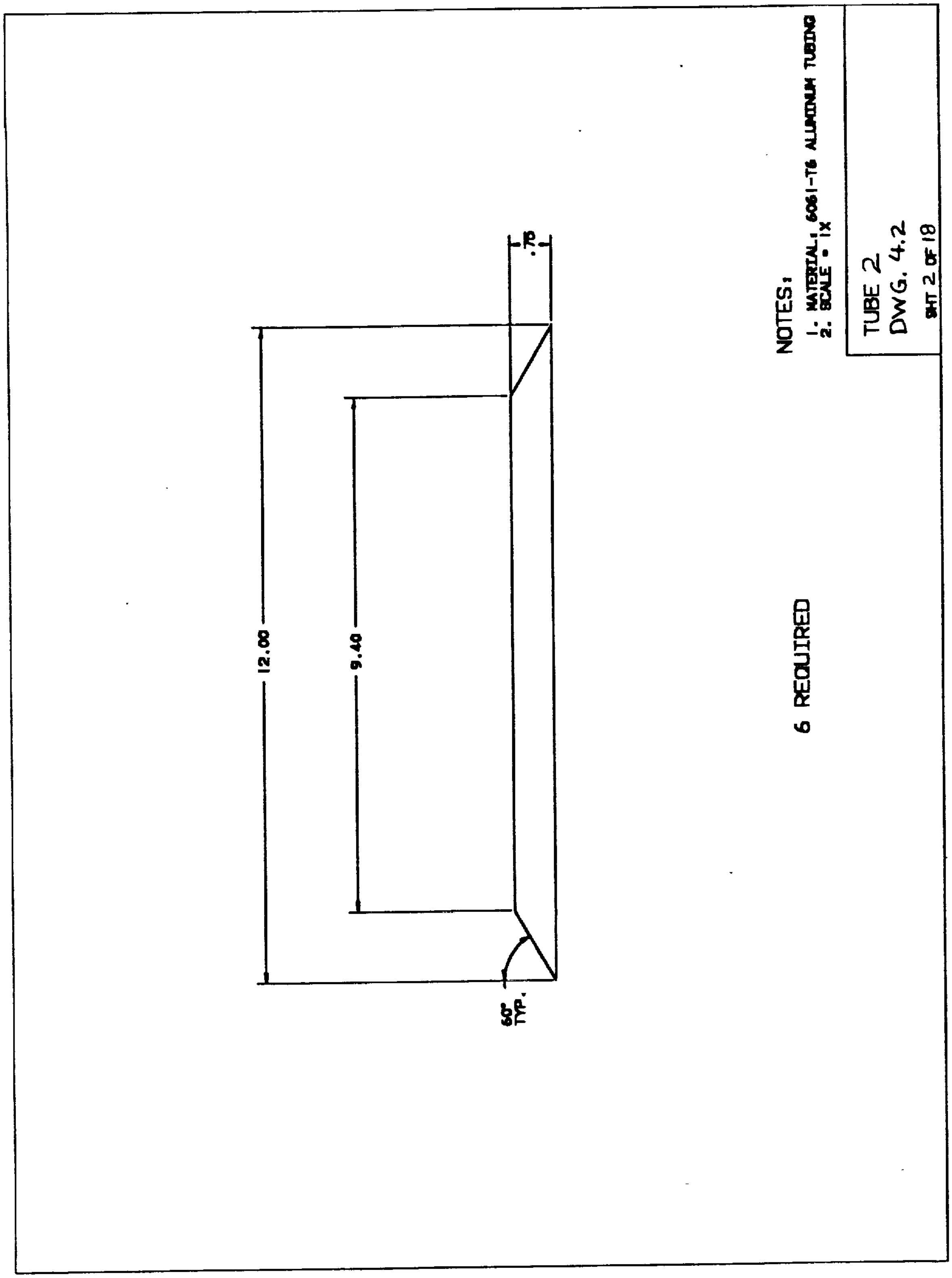
BILL OF MATERIALS

TUBING AND ROD - ALUMINUM 6061-T6

Tube No.	O.D.	Wall Thickness	Length	No. Reqd.
1	1	0.065	24	3
2	3/4	0.065	12	6
3	3/4	0.065	13	12
4	1	0.065	27-3/4	3
5	1	0.065	29-3/8	6
6	1	0.065	9	3
7	3/4	0.065	19	3
8	3/4	0.065	11-3/4	6
9	3/4	0.065	5-1/4	6
10	3/4	0.065	6-3/8	6
11	3/4	0.065	14-3/4	6
12	3/4	0.065	10-1/4	3
13	3/4	0.065	21-5/8	6
14	3/4	0.065	15-1/2	6
15	1	0.065	5-1/4	6
16	1	0.065	30-1/4	6
17	1	0.065	11	3
18	3/4	0.065	9	3
19	3/8	ROD	12	6
20	3/8	ROD	13-1/2	6
21	3/8	ROD	20-5/8	3

NOTE: All dimensions are in inches.


NOTES:
1. MATERIAL: 6061-T6 ALUMINUM.
2. SCALE = .5X
TUBE 1
DWG. 4.1
SHT 1 OF 18
24.00
20.84
60° TYP.
1" TUBE (REF.)
3 REQUIRED/UNIT


.75
12.00
9.40
60° TYP.
6 REQUIRED
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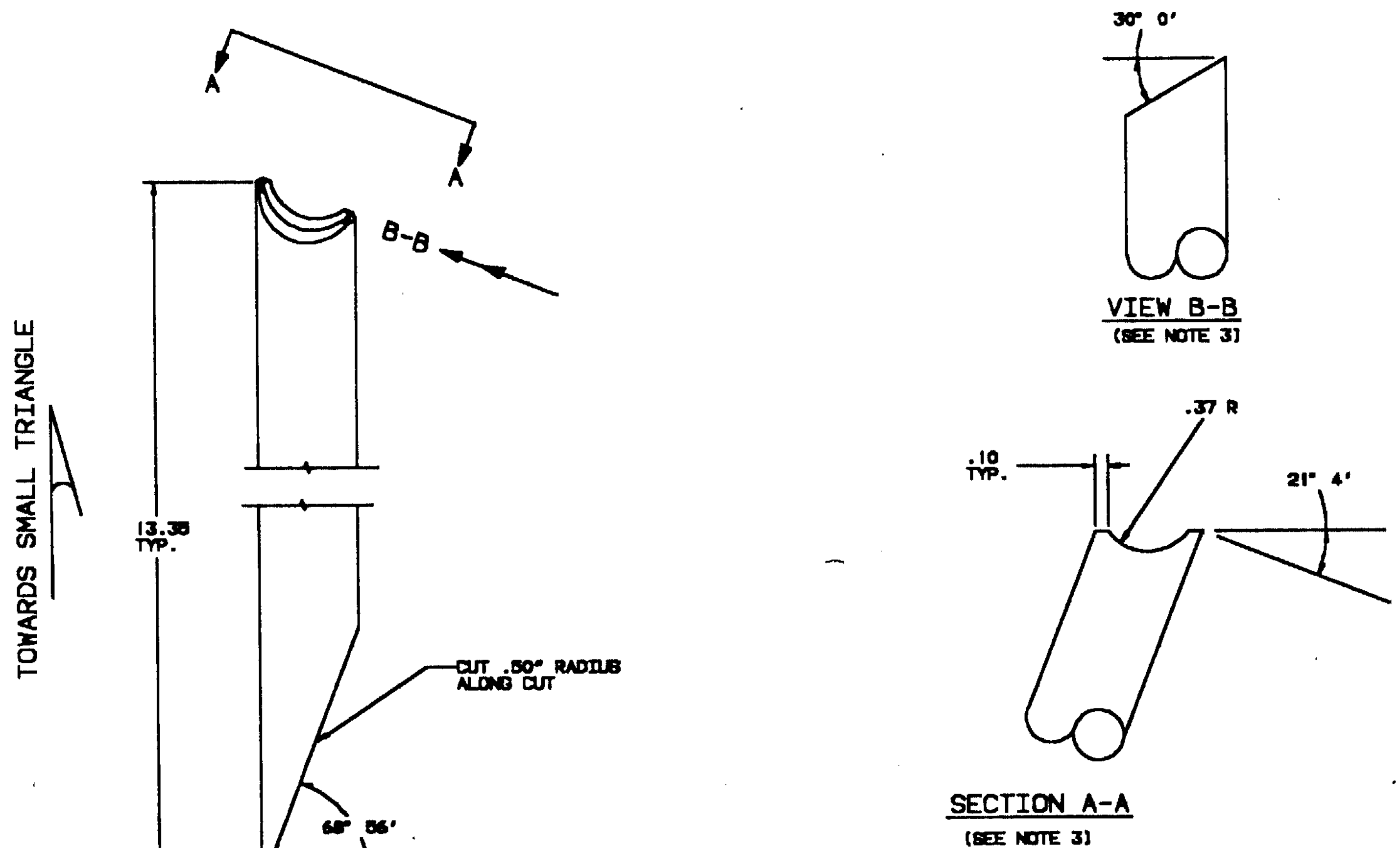
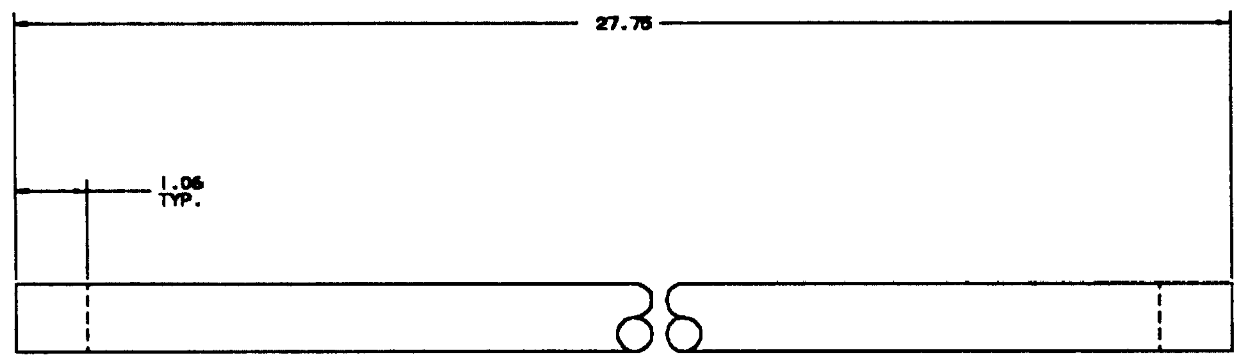
DWG. 4.2
SHT 2 OF 18



NOTES:

1. ALL MATERIAL 6061-T6 ALUMINUM.
2. SCALE = 2X
3. MAKE 30° CUT PERPENDICULAR TO 21°4' CUT.

2-6 REQUIRED/UNIT TUBE 3 SHT 3 OF 18 DWG. 4.3



3 REQUIRED

NOTES:

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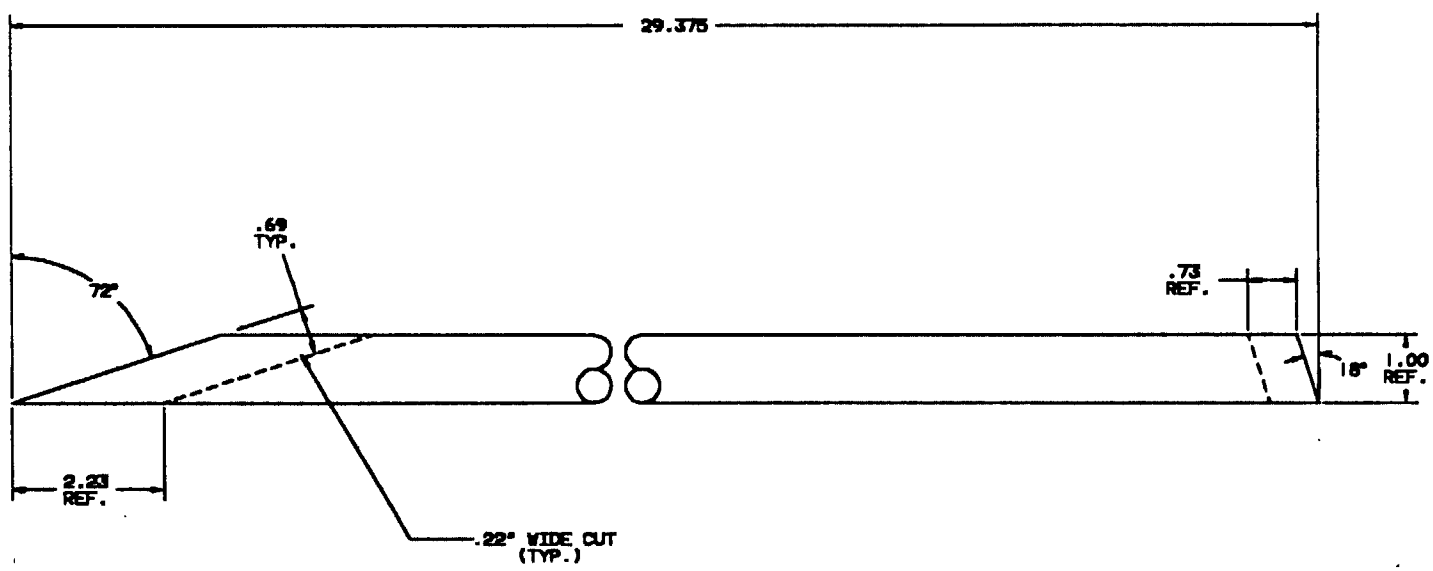
TUBE 4
DWG. 4.4
SHT 4 OF 18

A



6 REQUIRED

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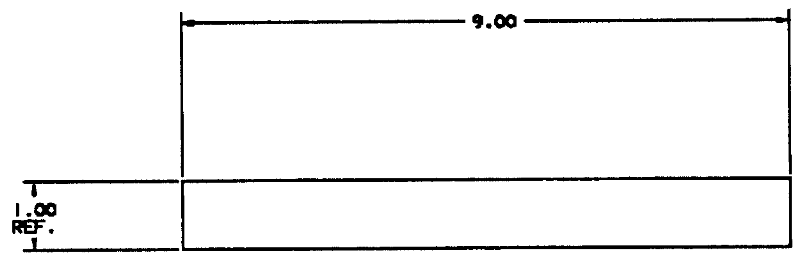
2. SCALE = 1X

TUBE 5
DWG. 4.5
SHT 5 OF 18



3 REQUIRED

NOTES:
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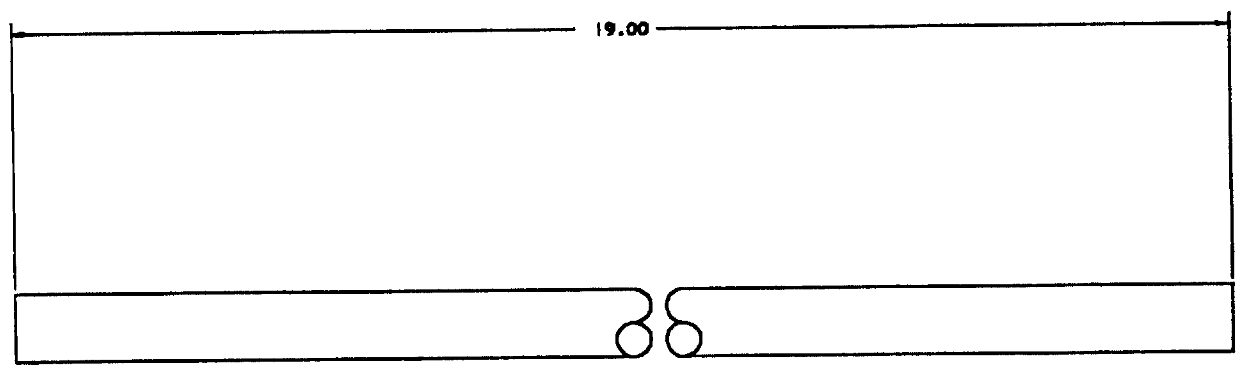
2. SCALE = 1X

TUBE 6
DWG. 4.6
SHT 6 OF 18



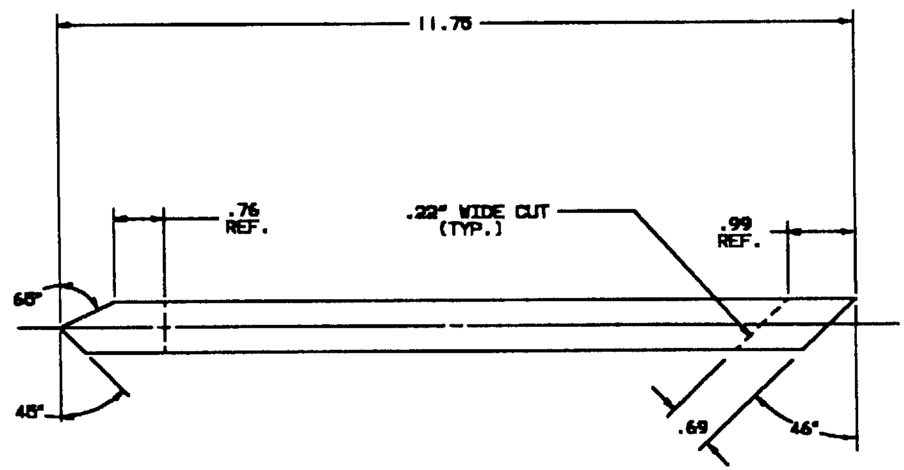
3 REQUIRED

NOTES:

1. ALL MATERIAL .75 DIA 6061-T6 ALUMINUM TUBING.
2. SCALE = 1X

TUBE 7
DWG. 4.7
SHT 7 OF 18

B



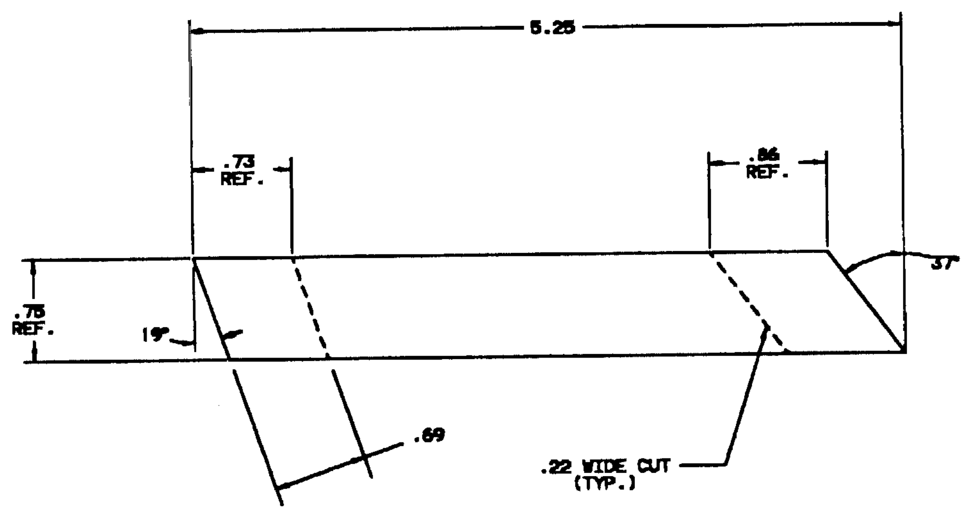
6 REQUIRED

NOTES:

1. ALL MATERIAL .76 DIA 6061-T6 ALUMINUM TUBING.
2. SCALE = 1X

TUBE 8
DWG. 4.8
SHT 8 OF 18

ORIGINAL PAGE IS
OF POOR QUALITY

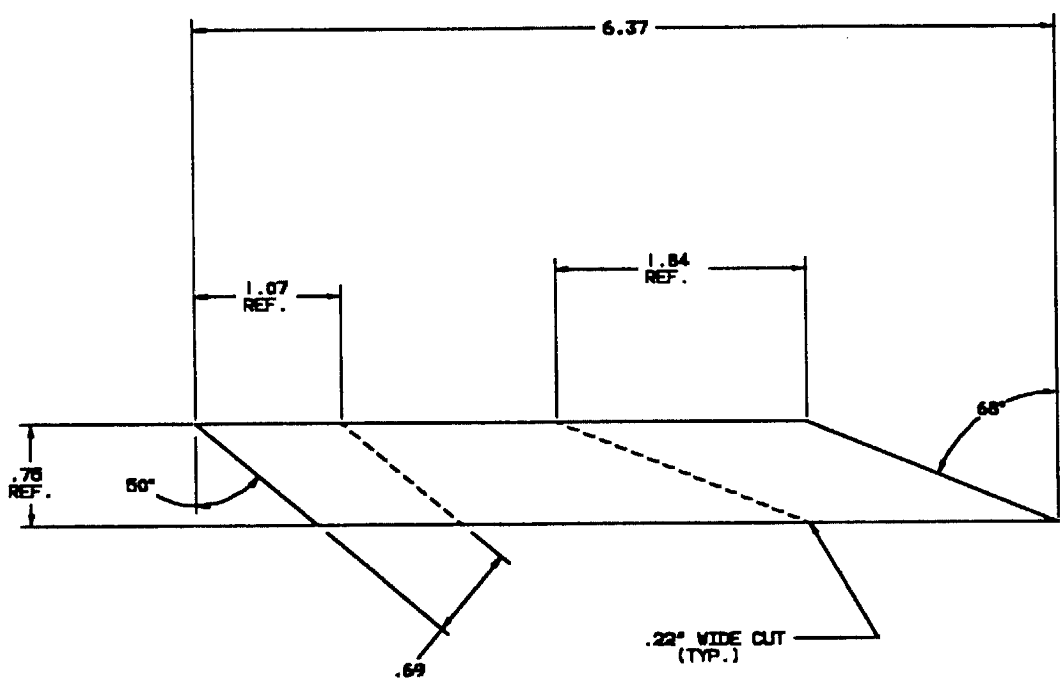


6 REQUIRED

NOTES:

1. MATERIAL: .75 DIA 6061-T6 ALUMINUM TUBING
2. SCALE = 2X

TUBE 9
DWG. 4.9
SHT 9 OF 18

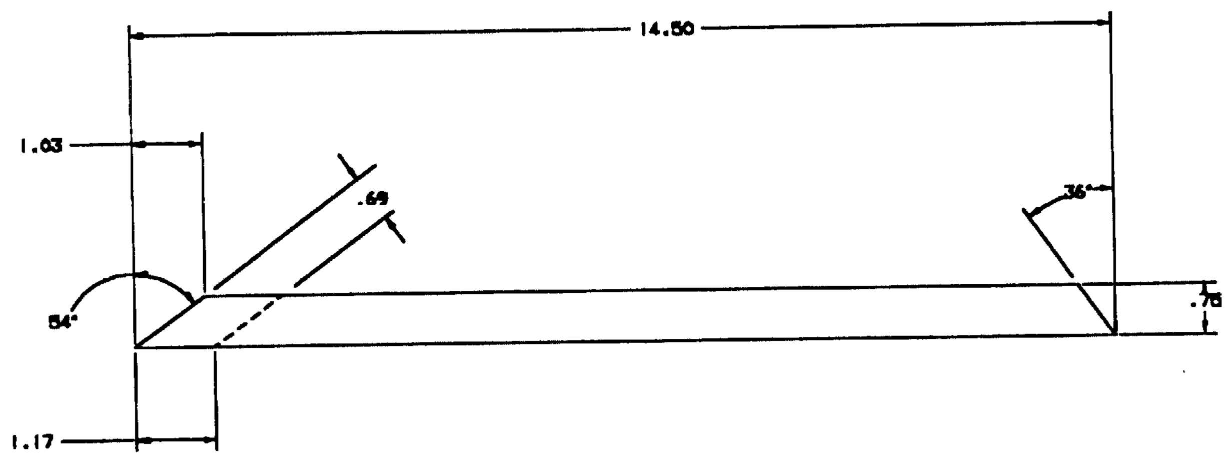


6 REQUIRED

NOTES:

1. ALL MATERIAL .75 DIA 6061-T6 ALUMINUM TUBING.
2. SCALE = 2X

TUBE 10
DWG. 4,10
SHT 10 OF 18

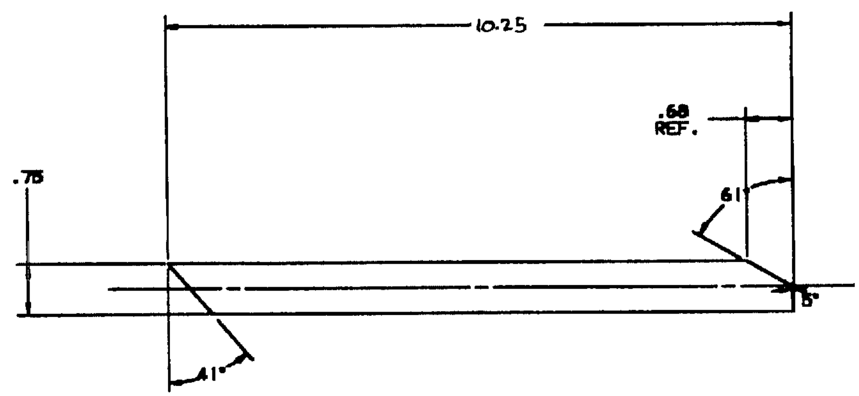


6 REQUIRED

NOTES:

1. MATERIAL: 6061-T6 ALUMINUM TUBING
2. SCALE = 1X

TUBE 11
DWG. 4.11
SHT 11 OF 18

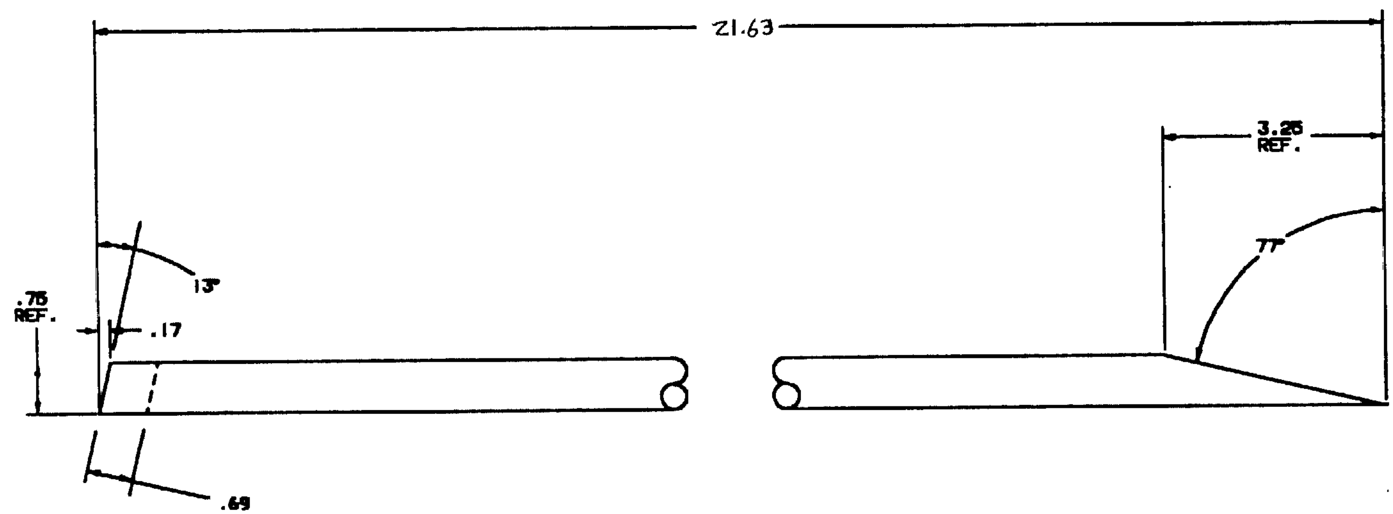


3 REQUIRED

NOTES:

1. ALL MATERIAL .75 DIA 6061-T6 ALUMINUM TUBING.
2. SCALE = 1X

TUBE 12
DWG. 4.12
SHT 12 OF 18

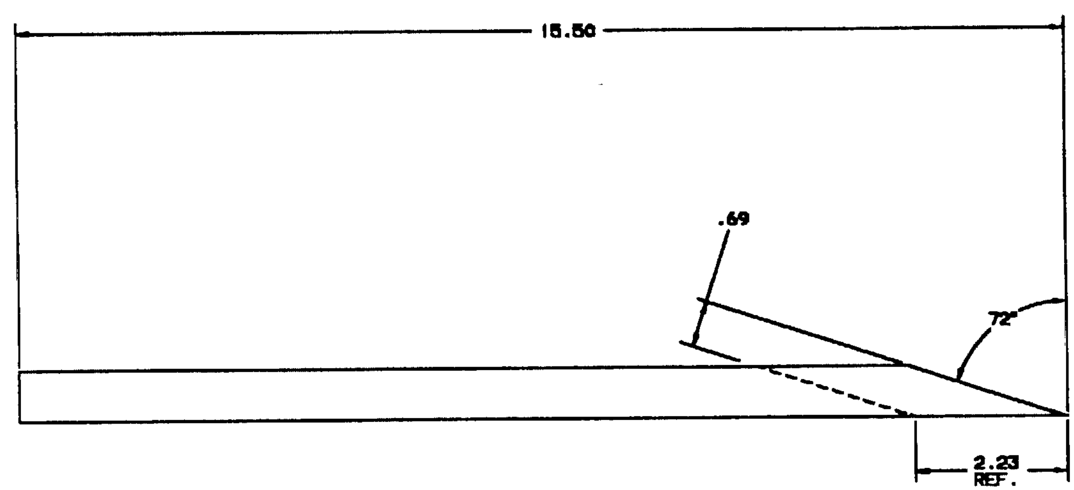


6 REQUIRED

NOTES:

1. ALL MATERIAL .75 DIA 6061-T6 ALUMINUM TUBING.
2. SCALE = 1X

TUBE 13
DWG. 4.13
SHT 13 OF 18

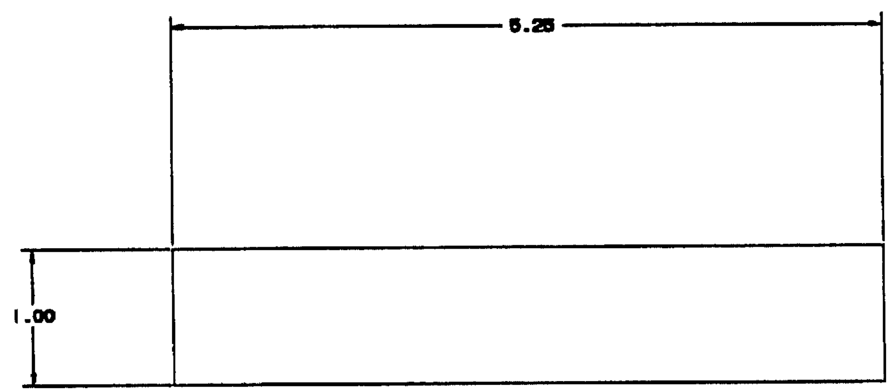


6 REQUIRED

NOTES:

1. ALL MATERIAL .75 DIA 6061-T6 ALUMINUM TUBING.
2. SCALE = 1X

TUBE 14
DWG 4.14
SHT 14 OF 18

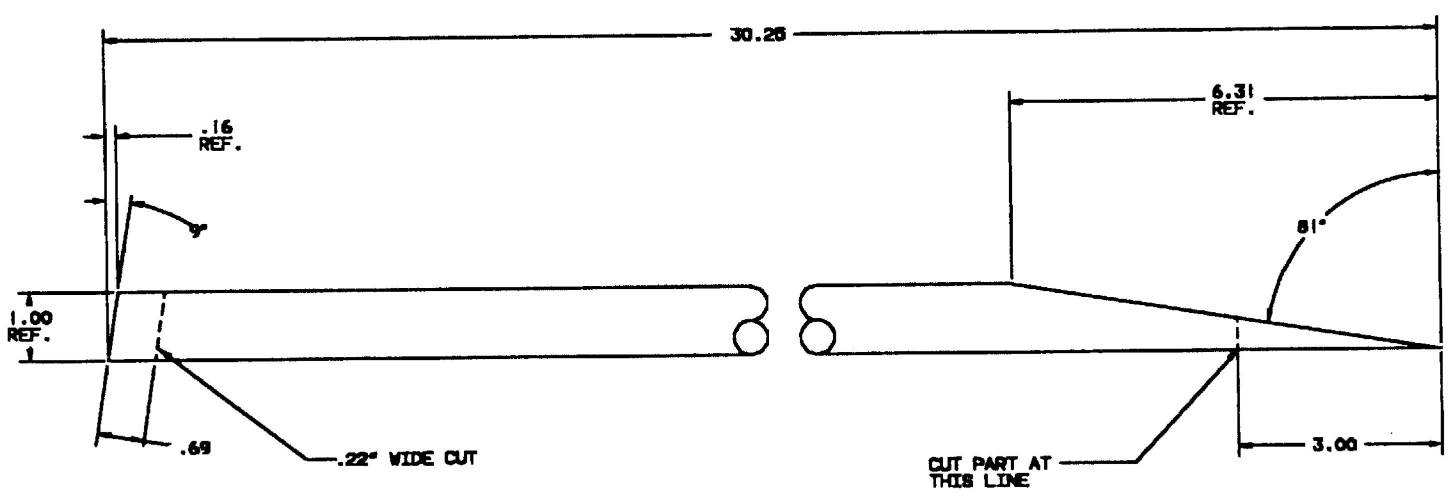


6 REQUIRED

NOTES:

1. MATERIAL: 6061-T6 ALUMINUM TUBING
2. SCALE = 2X

TUBE 15
DWG 4.15
SHT 15 OF 18



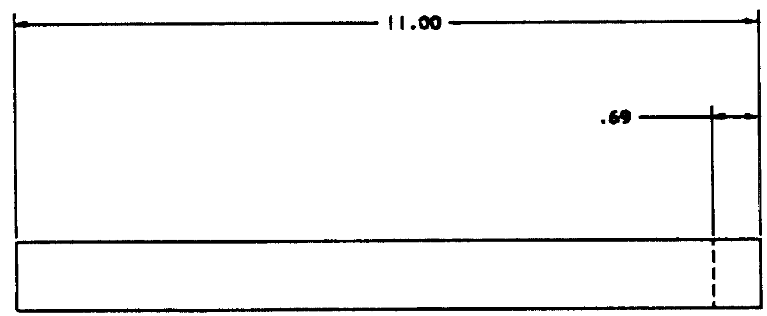
NOTES:

1. ALL MATERIAL 1.00 DIA 6061-T6 ALUMINUM TUBING.
2. SCALE = 1X

6 REQUIRED

TUBE 16
DWG. 4.16
SHT 16 OF 18

K

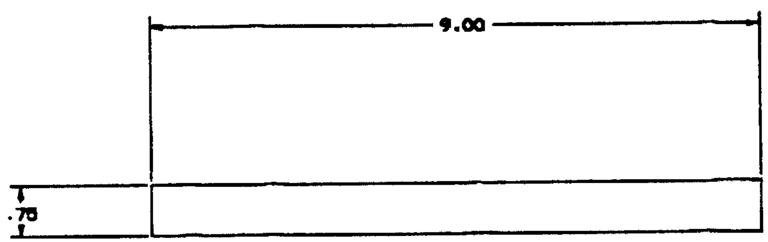


3 REQUIRED

NOTES:

1. ALL MATERIAL 1.00 DIA 6061-T6 ALUMINUM TUBING.
2. SCALE = 1X

TUBE 17
DWG 4.17
SHT 17 OF 18

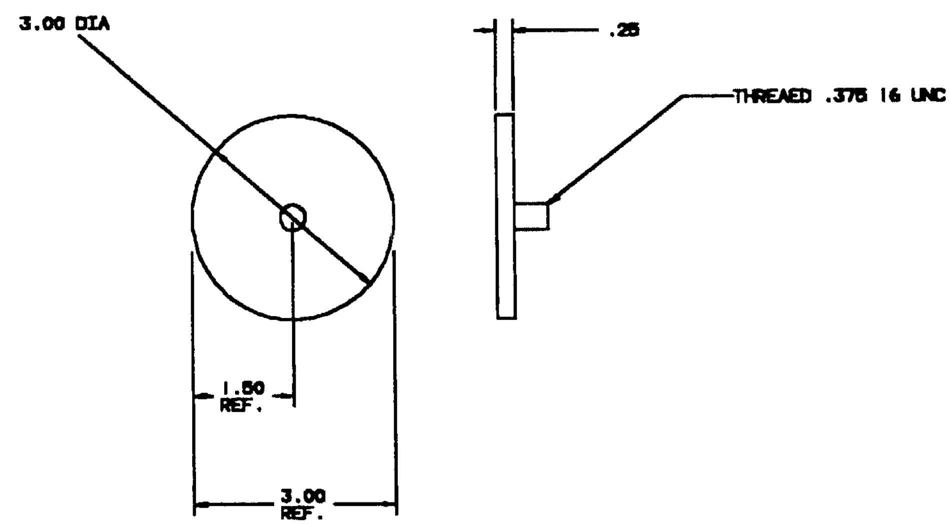


3 REQUIRED

NOTES:

1. ALL MATERIAL .75 DIA 6061-T6 ALUMINUM TUBING.
2. SCALE = 1X

TUBE 18
DWG 4.18
SHT 18 OF 18

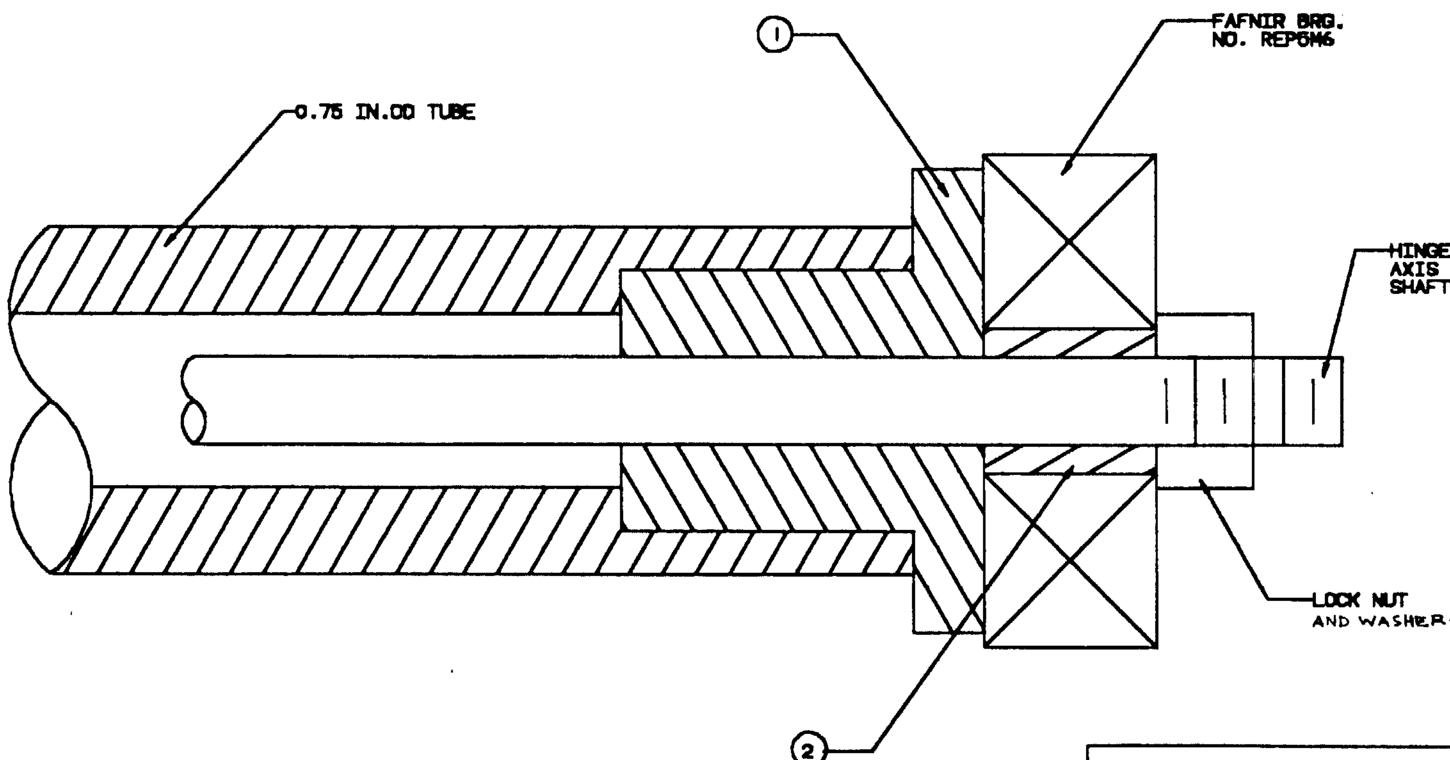


NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

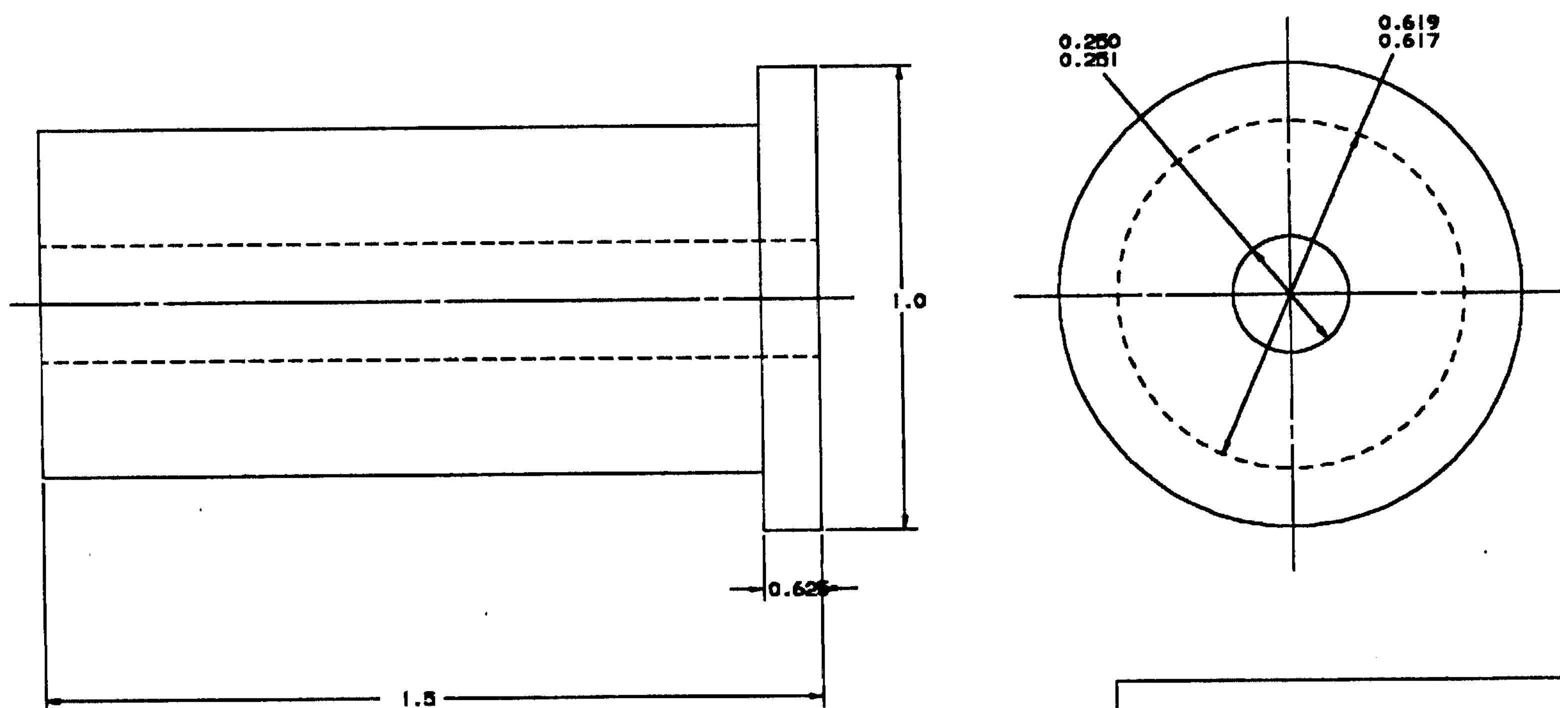
TIBIA FOOT
DWG. 5
SHT 1 OF 1

HINGES



HINGE JOINT ASSY

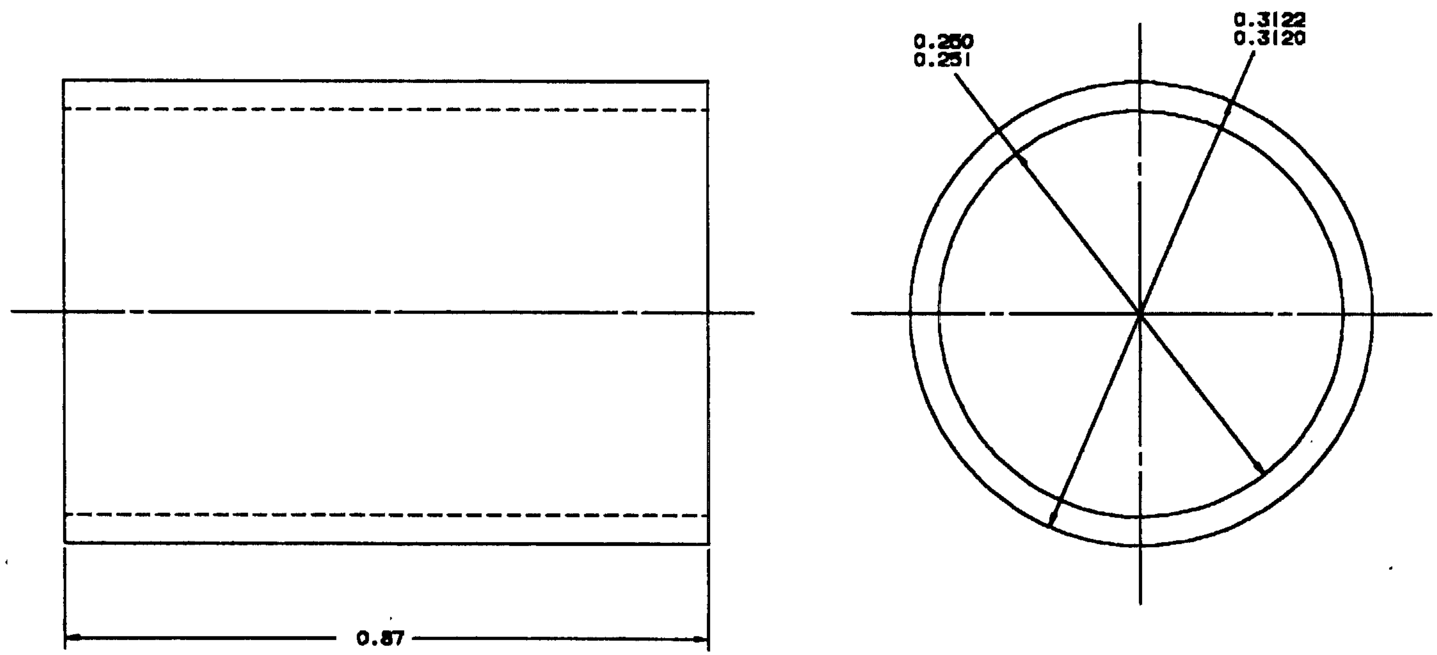
DWG 6.1



① HINGE SHAFT SLEEVE

MATERIAL: ALUMINUM 6061 T6

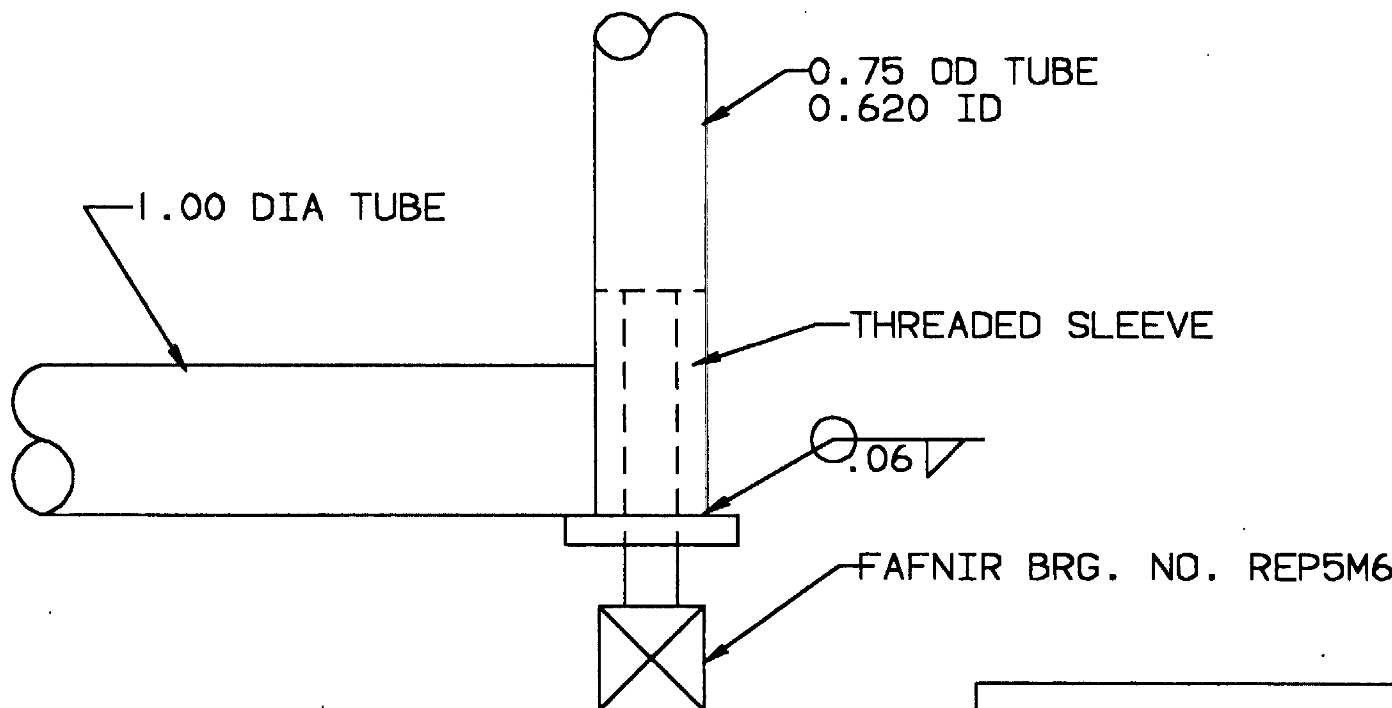
DWG 6.1 A



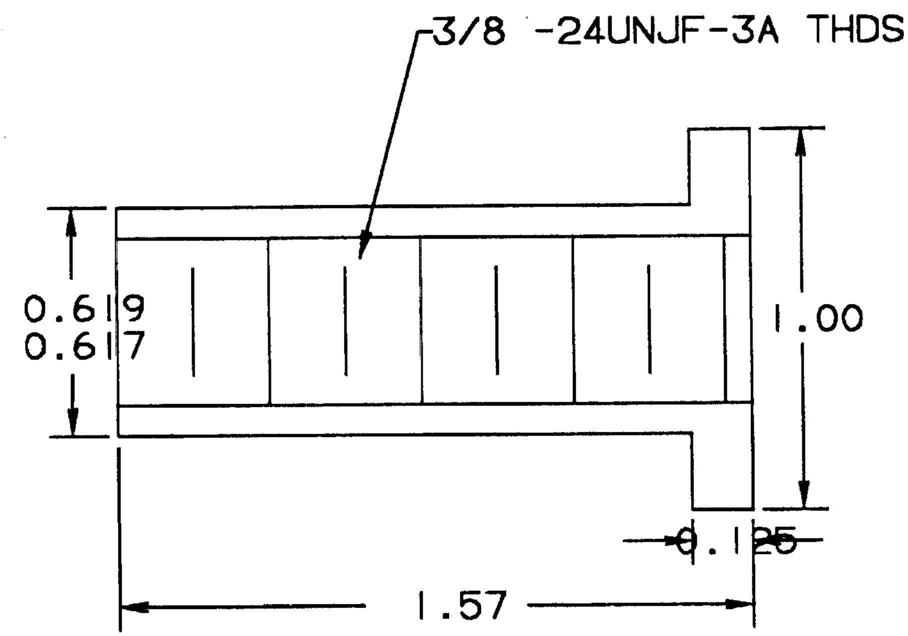
② BEARING SLEEVE

MATERIAL: BEARING BRONZE

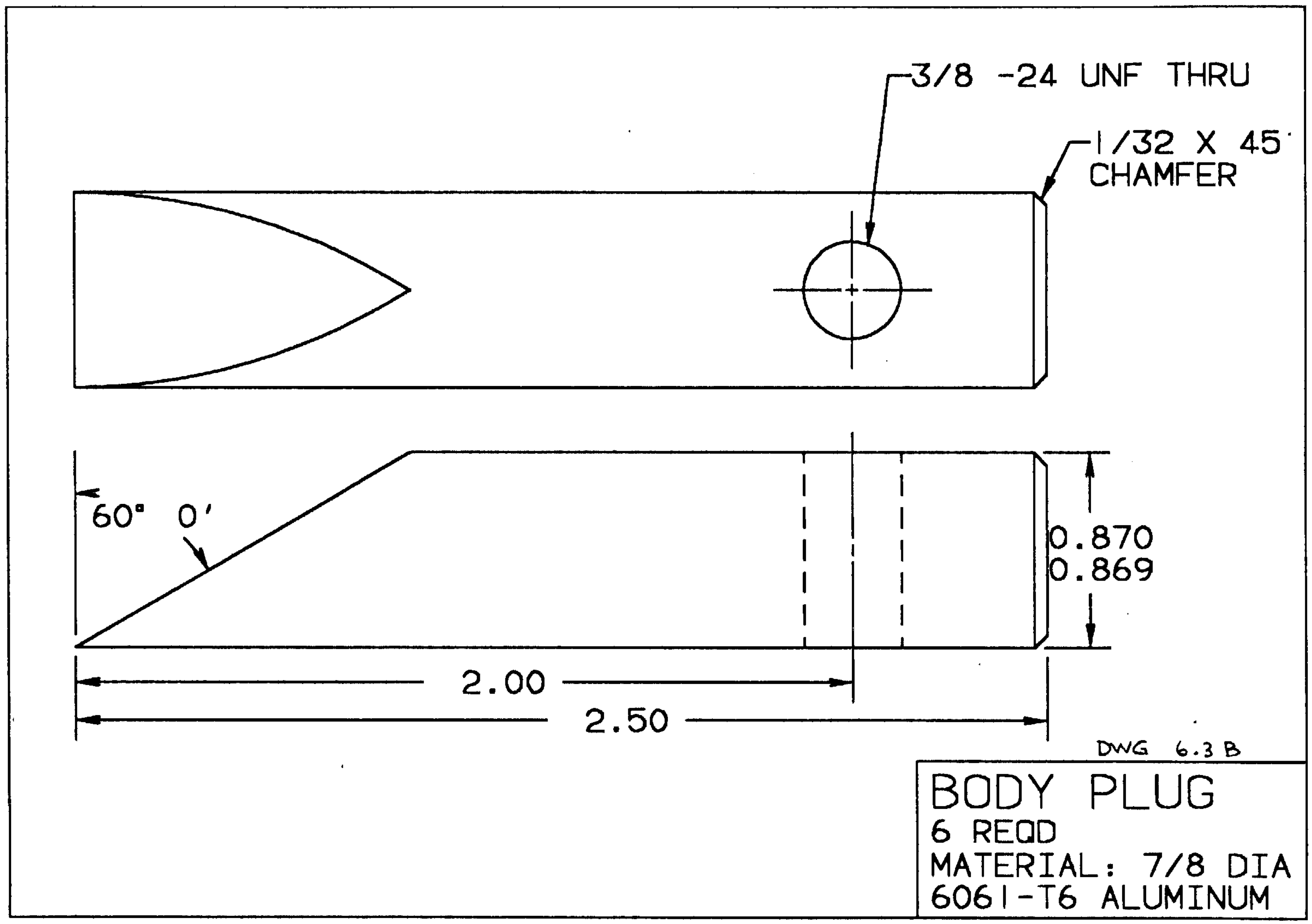
DWG 6.1 B

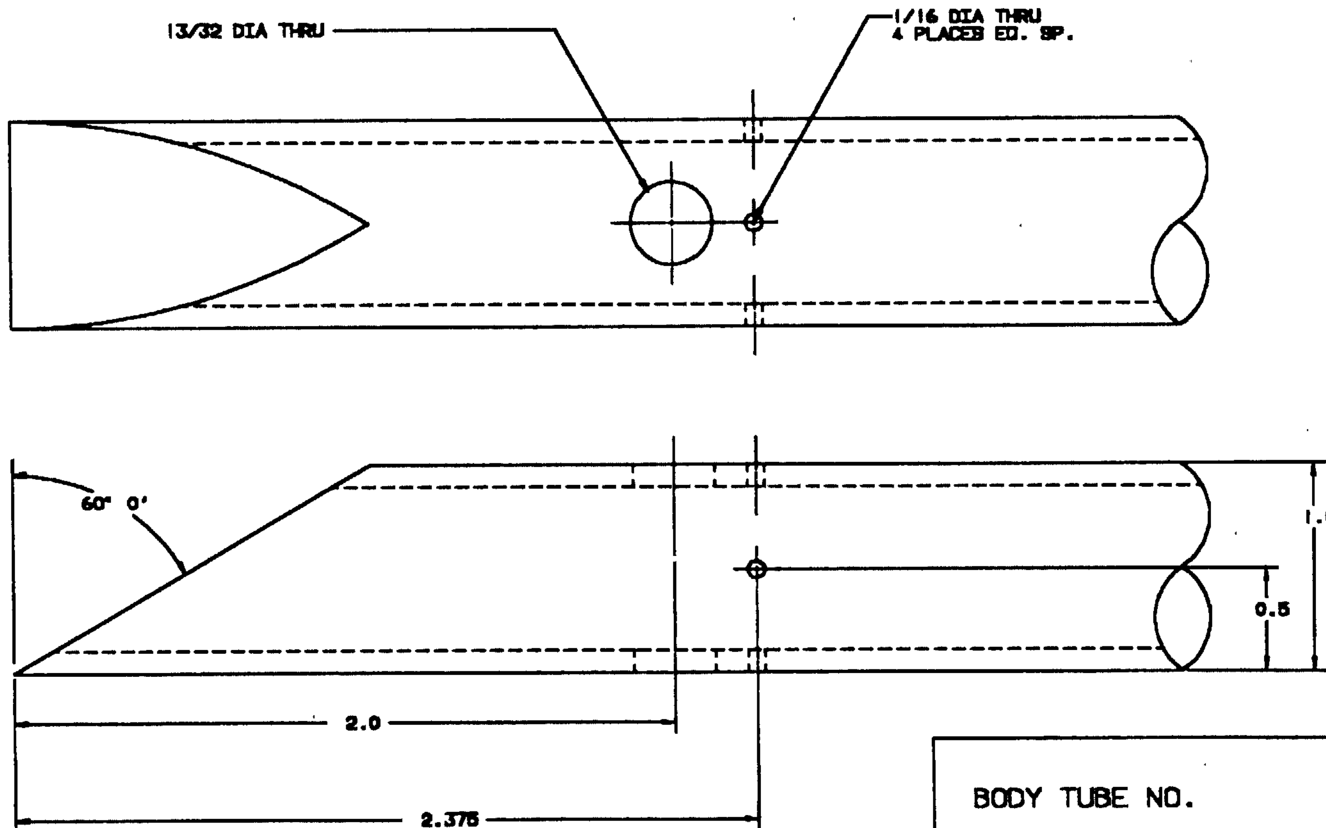


KNEE JOINT
FEMUR-TIBIA
CONNECTION
DWG 6.2



KNEE SLEEVE
NOTE: LC7 FIT ON
OD OF THD BUSHING
MATL: ALUM 6061-T6
DWG 6.2 A

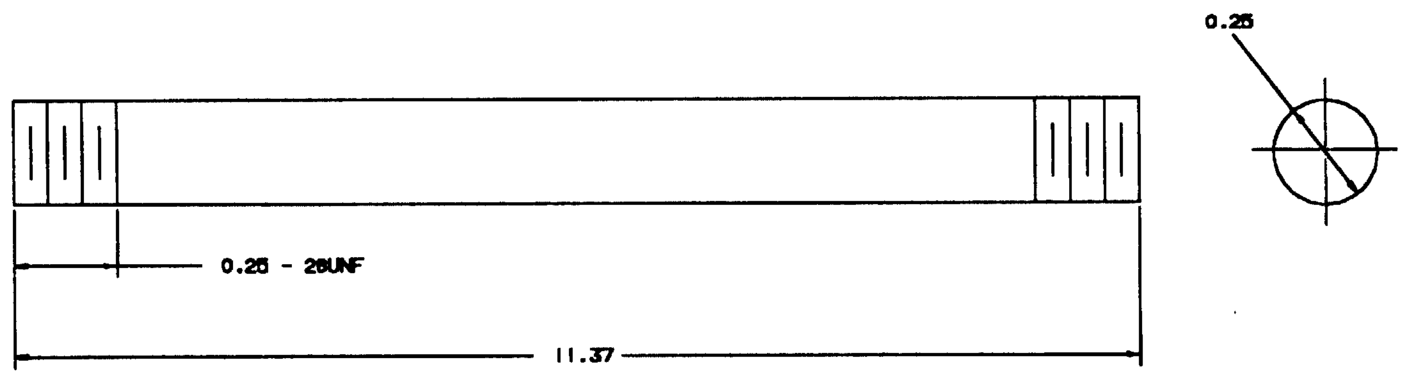

3/8 -24 UNF THRU
1/32 X 45°
CHAMFER
60° 0′
0.870
0.869
2.00
2.50
DWG 6.3 B
BODY PLUG
6 REQD
MATERIAL: 7/8 DIA
6061-T6 ALUMINUM



BODY TUBE NO.

NOTE: SPOT WELD BODY
PLUG IN TUBE

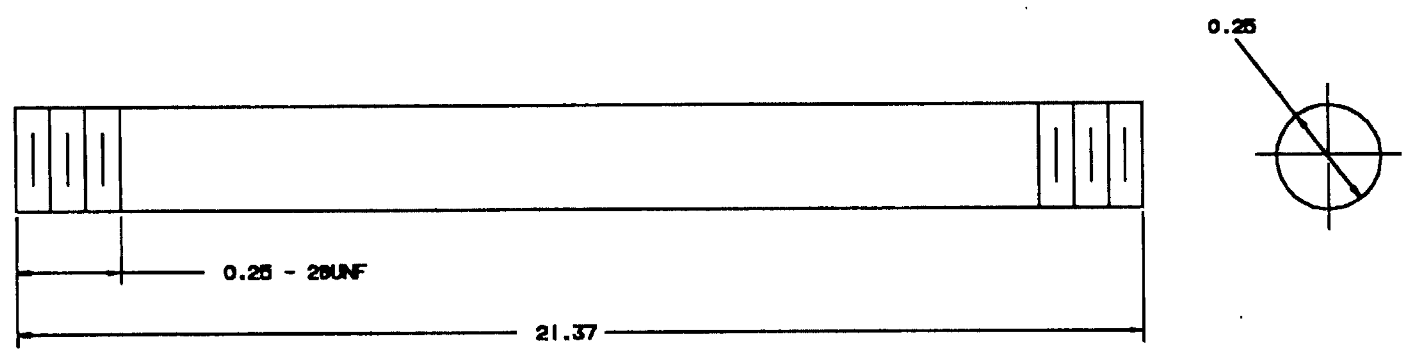
DWG 6.3 A



TIBIA KNEE JOINT SHAFT

MATERIAL: ALUMINUM 6061 T6

DWG 6.4 A

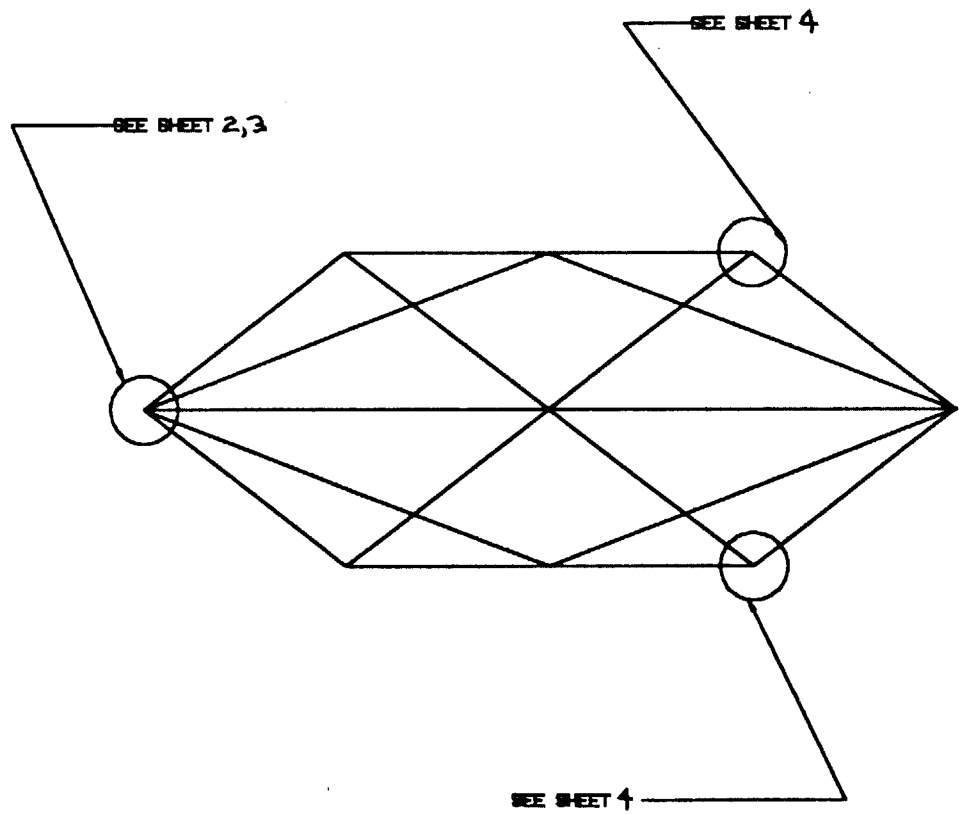


FEMUR HIP JOINT SHAFT

MATERIAL: ALUMINUM 6061 T6

DWG 6.4B

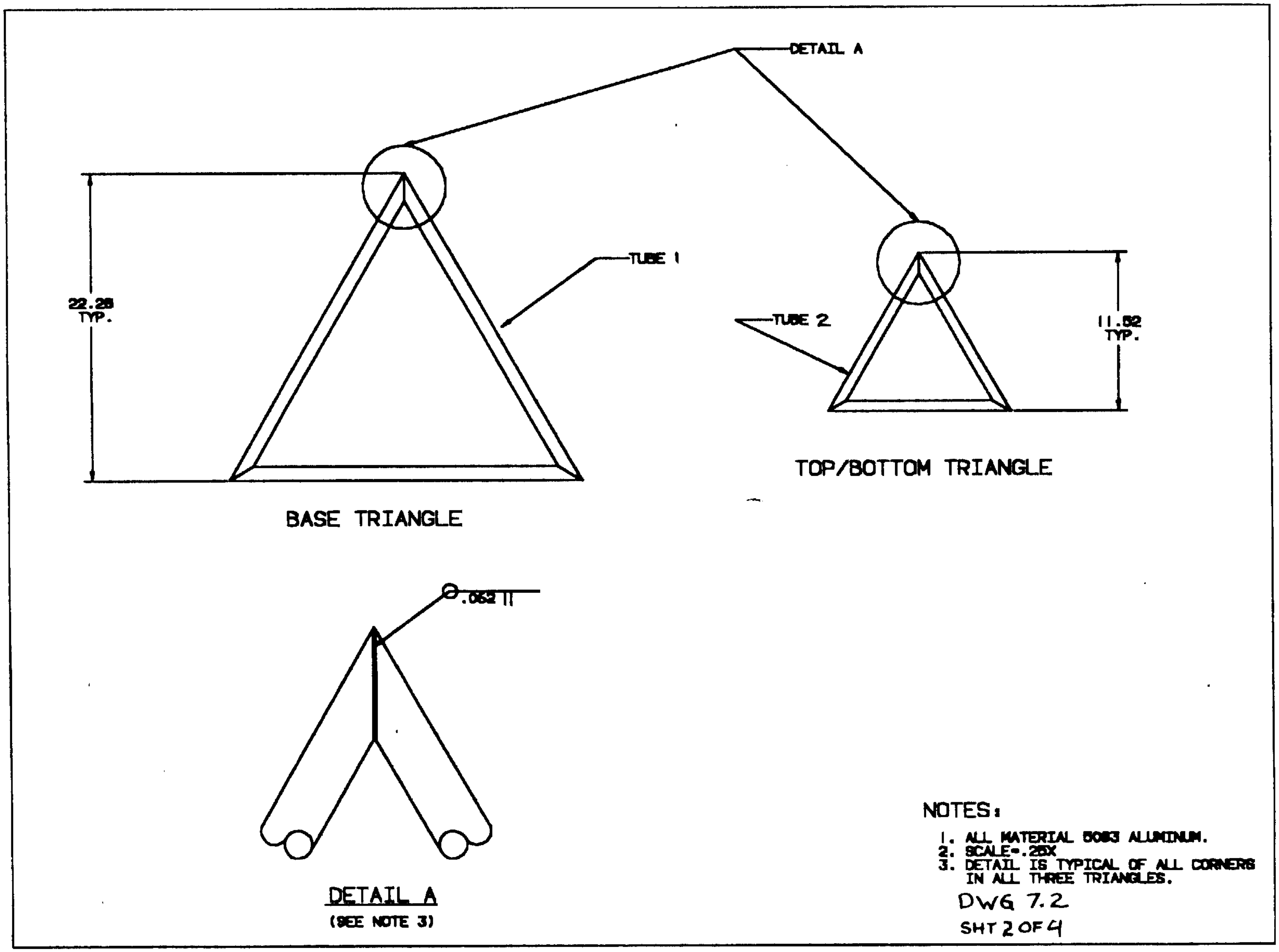
WELDMENTS

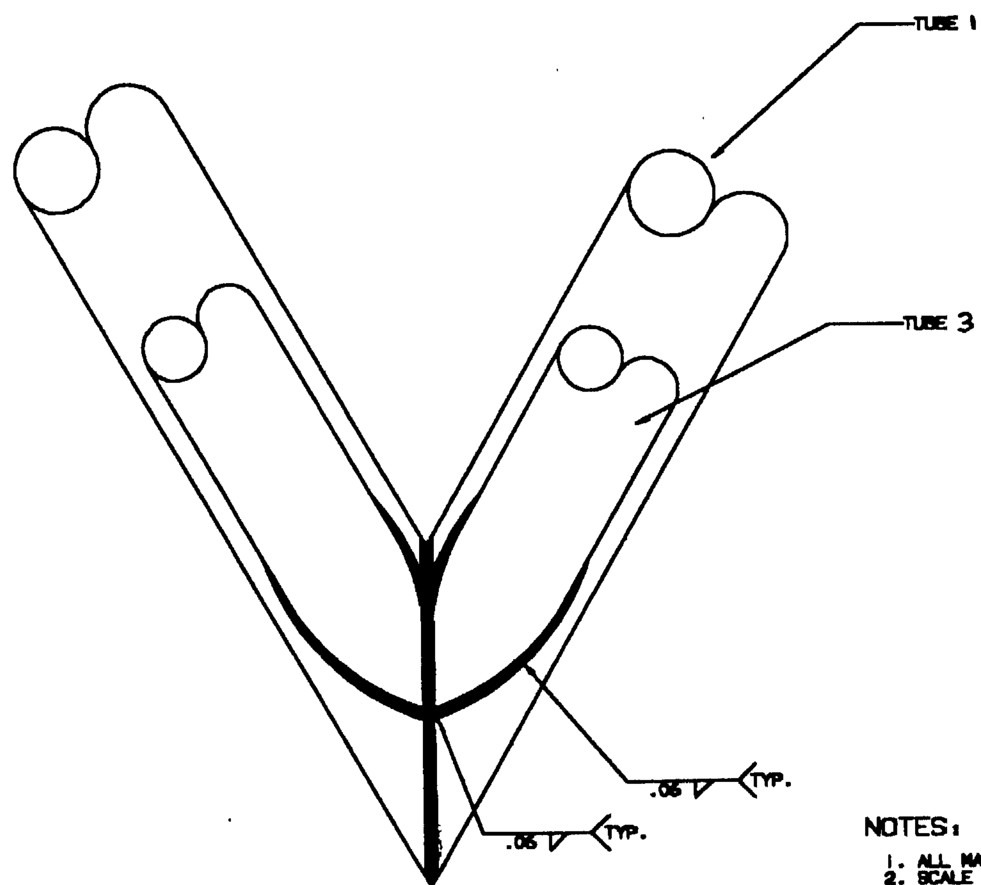


NOTES:

1. ALL MATERIAL 6061-T6 ALUMINUM.
2. SCALE = .25X

BODY WELDING DETAILS
DWG 7.1
SHT 1 OF 4

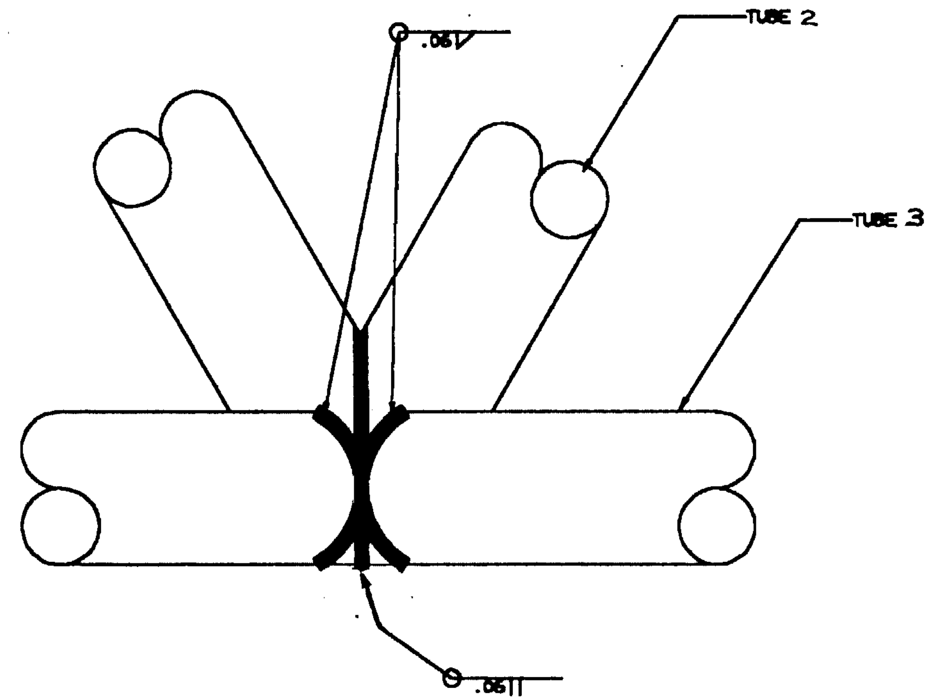

DETAIL A
TUBE 1
22.28
TYP.
BASE TRIANGLE
TUBE 2
11.52
TYP.
TOP/BOTTOM TRIANGLE
.062
DETAIL A
(SEE NOTE 3)
NOTES:
1. ALL MATERIAL 5083 ALUMINUM.
2. SCALE=.25X
3. DETAIL IS TYPICAL OF ALL CORNERS IN ALL THREE TRIANGLES.
DWG 7.2
SHT 2 OF 4



NOTES:

1. ALL MATERIAL 6061-T6 ALUMINUM.
2. SCALE = 2.5X
3. WELDS ARE TYPICAL OF TOP AND BOTTOM SIDE OF WELDS OF ALL THREE CORNERS OF BASE TRIANGLE.

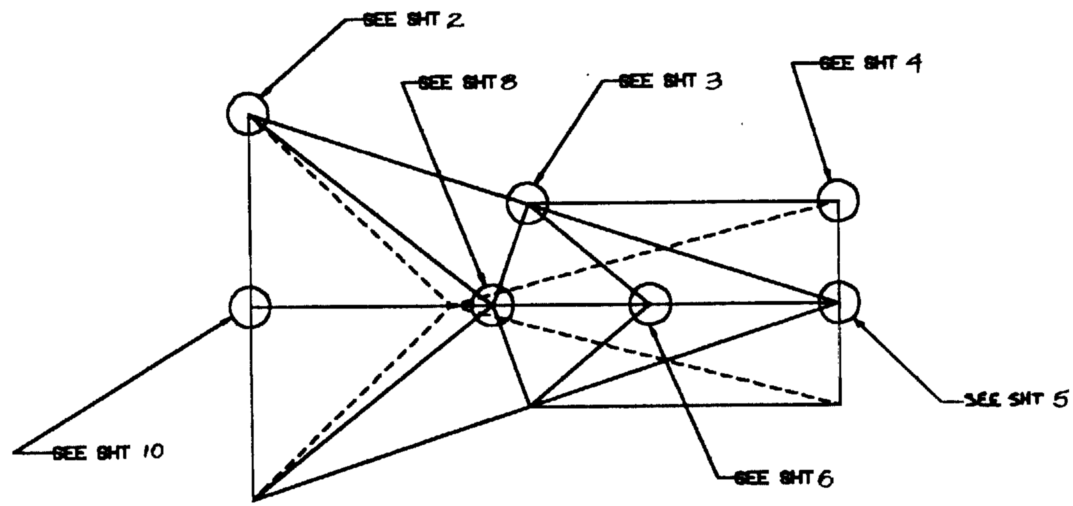
BODY DETAILS
BASE TRIANGLE
WELDING DETAIL
SHT. 3 OF 4
DWG 7.3



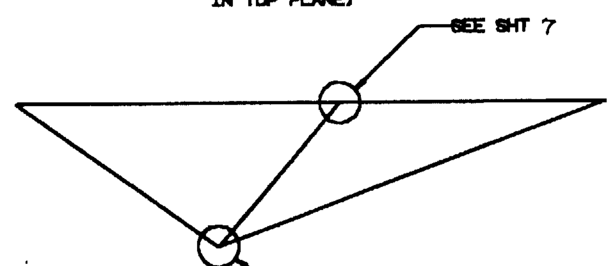
NOTES:

1. ALL MATERIAL 6061-T6 ALUMINUM.
2. SCALE = 3X
3. WELDS ARE TYPICAL FOR ALL CORNERS OF TOP AND BOTTOM TRIANGLES.

BODY DETAILS
TOP/BOTTOM TRIANGLE
WELDING DETAIL
SHT 4 OF 4
DWG 7.4



TOP VIEW
(DOTTED LINES NOT IN TOP PLANE)



SIDE VIEW

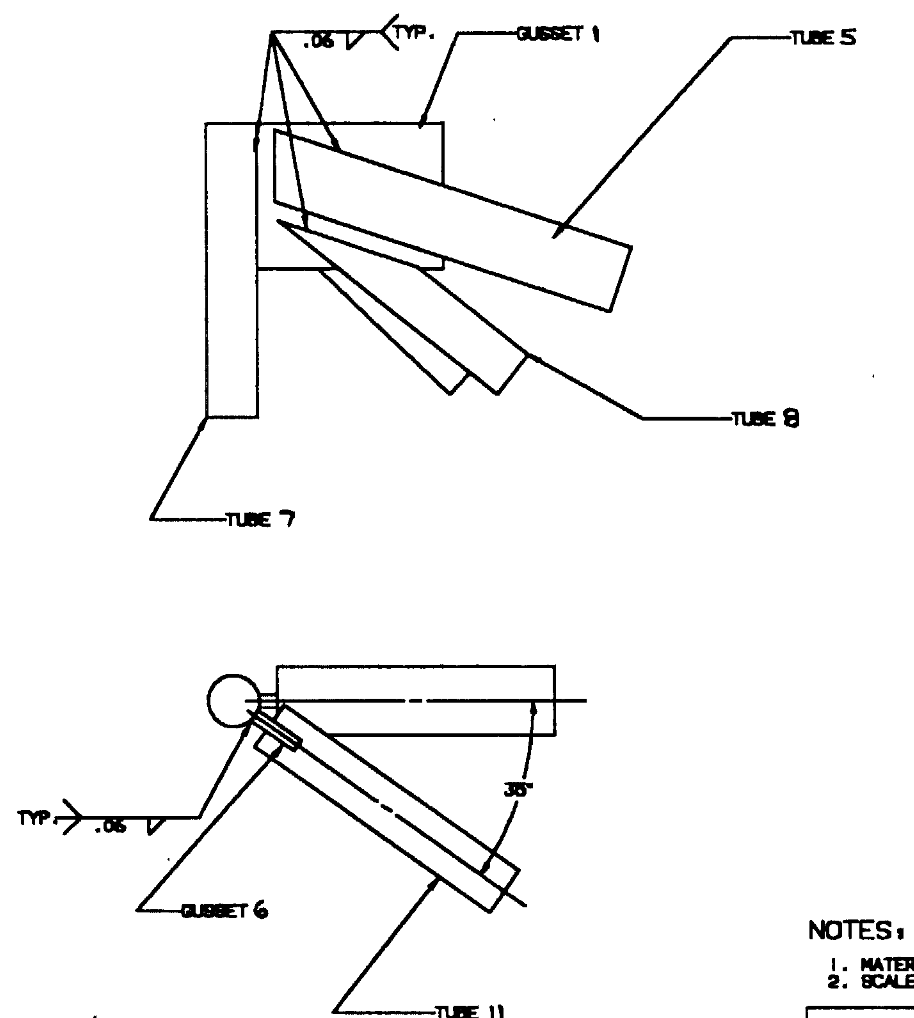
NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = .25

FEMUR WELDING DETAILS

DWG 8.1

SHT 1 OF 10



NOTES:

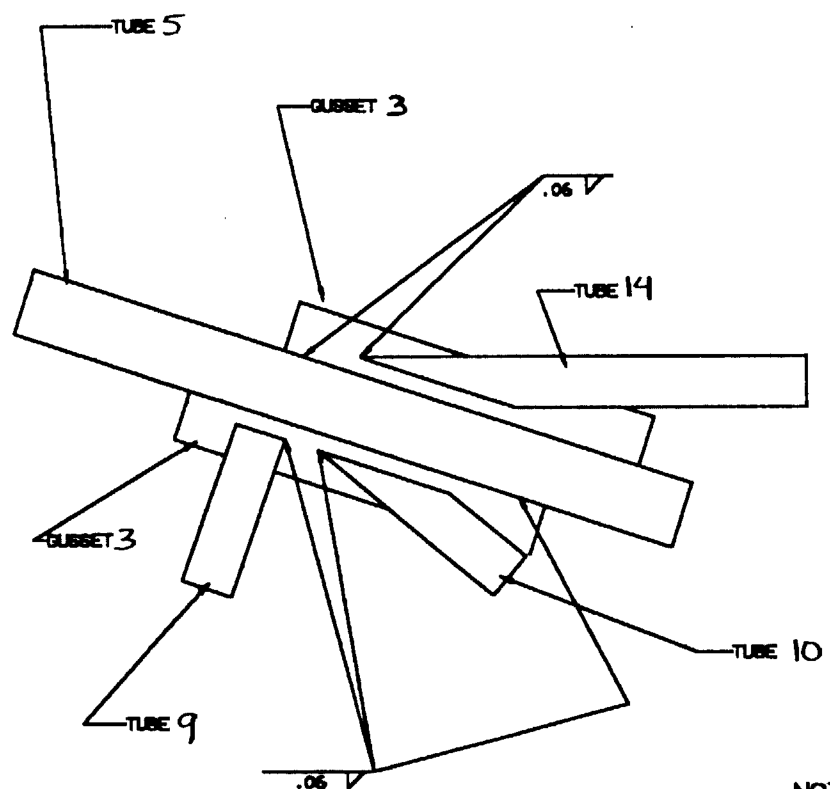
1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

FEMUR WELD

DWG 8.2

SHT 2 OF 10

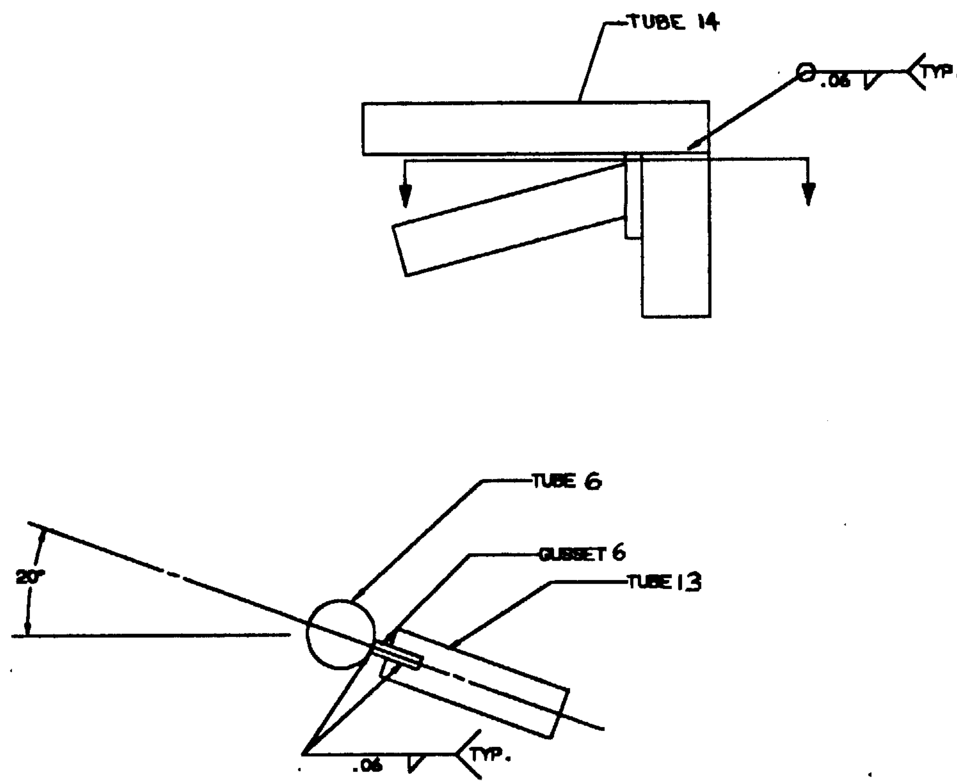
ORIGINAL PAGE IS OF POOR QUALITY



NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

FEMUR WELD
DWG 8.3
SHT 3 OF 10



SECTION

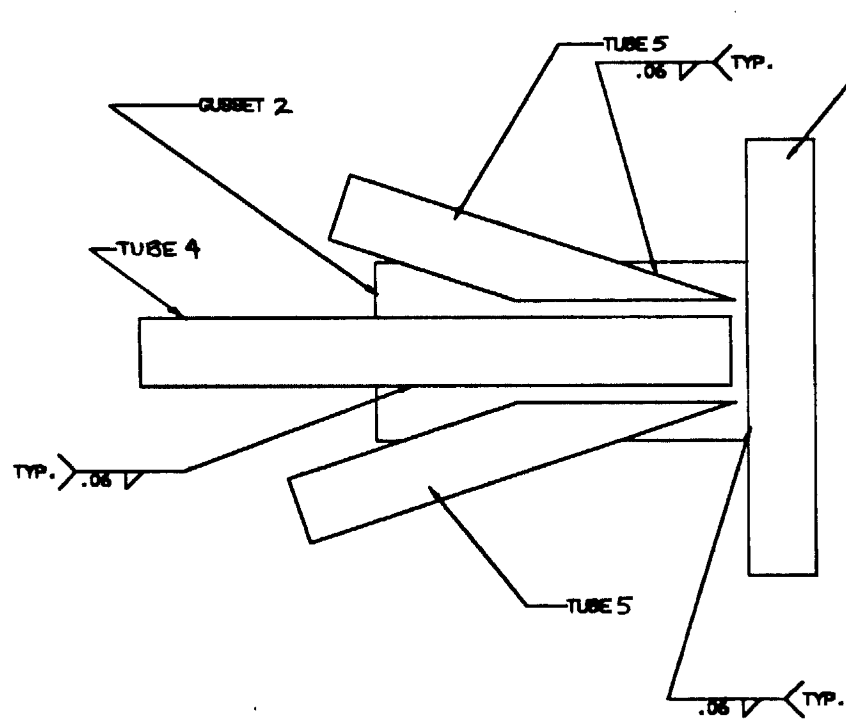
NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

FEMUR WELD

DWG 8.4

SHT 4 OF 10

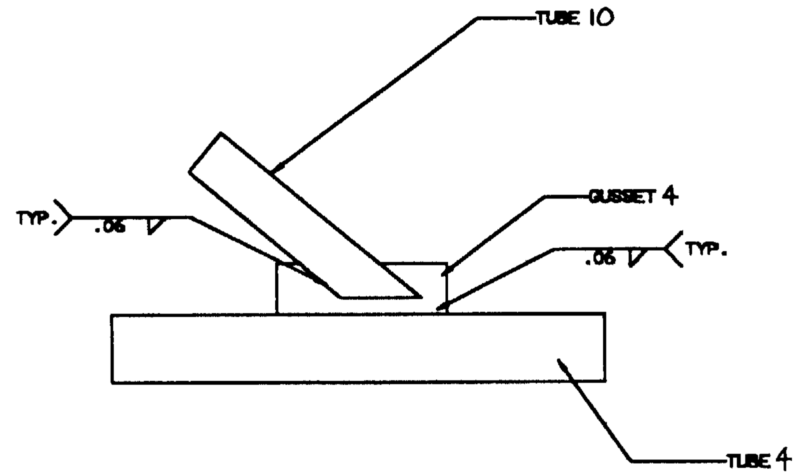


NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

FEMUR WELD
DWG 8.5
SHT 5 OF 10

ORIGINAL PAGE IS
OF POOR QUALITY



NOTES:

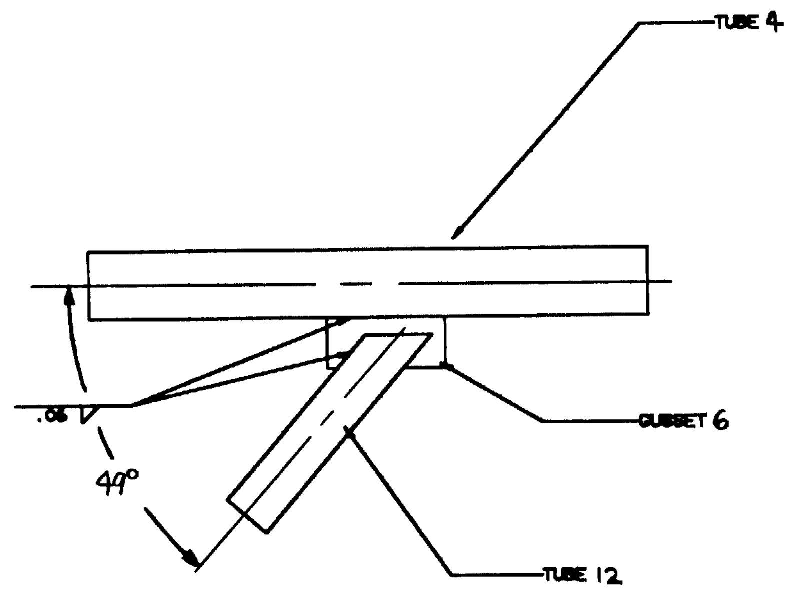
1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

FEMUR WELD

DWG 8.6

SHT 6 OF 10

ORIGINAL PAGE IS
OF POOR QUALITY



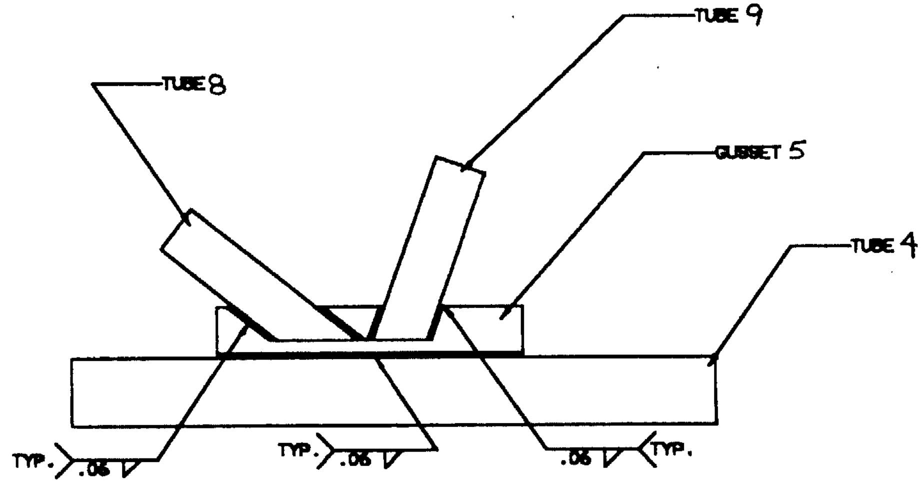
NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

FEMUR WELD

DWG 8.7

SHT 7 OF 10



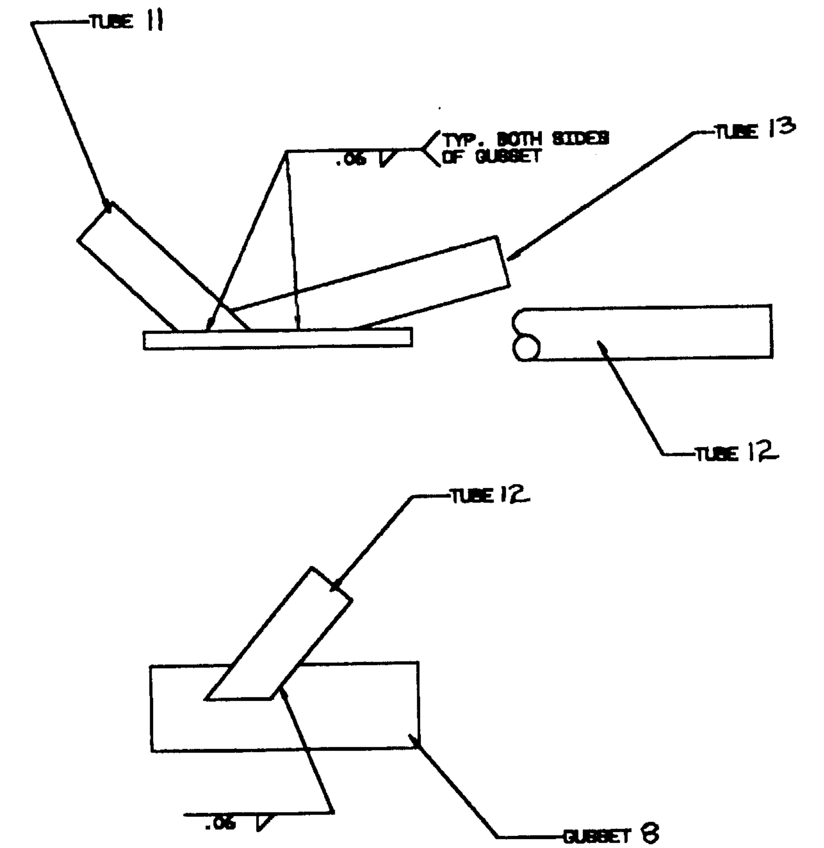
NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

FEMUR WELD

DWG 8.8

SHT 8 OF 10



NOTES:

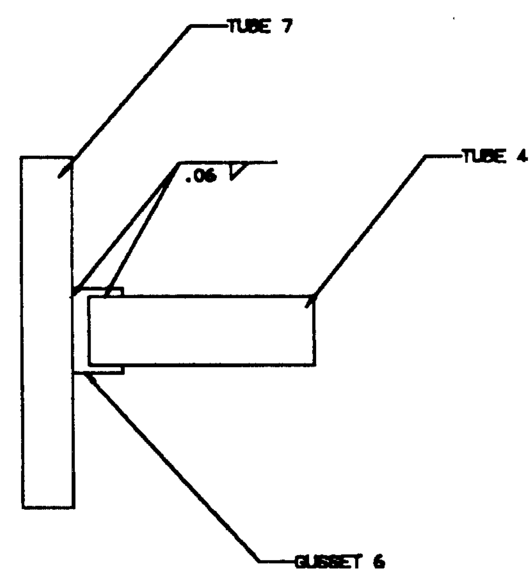
1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

FEMUR WELD

DWG 8.9

SHT 9 OF 10

ORIGINAL PAGE IS OF POOR QUALITY

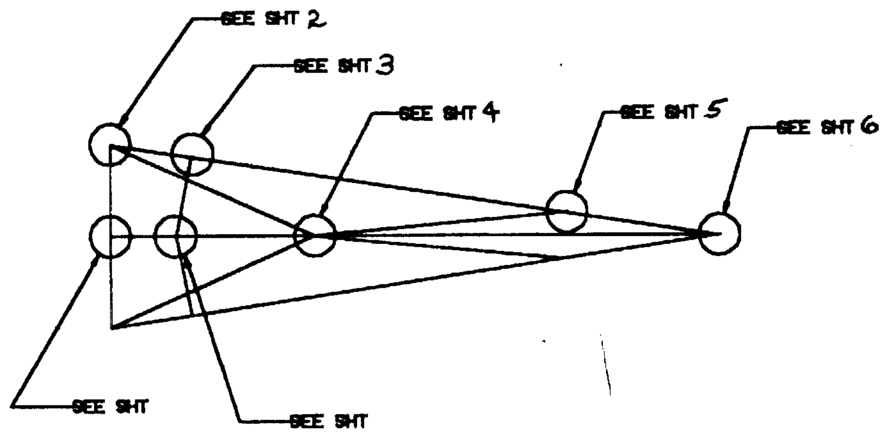


NOTES:

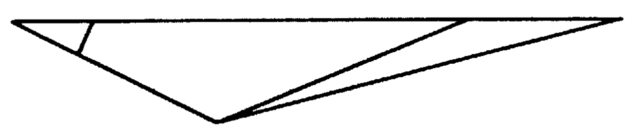
1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

FEMUR WELD

SHT 10 OF 10



TOP VIEW

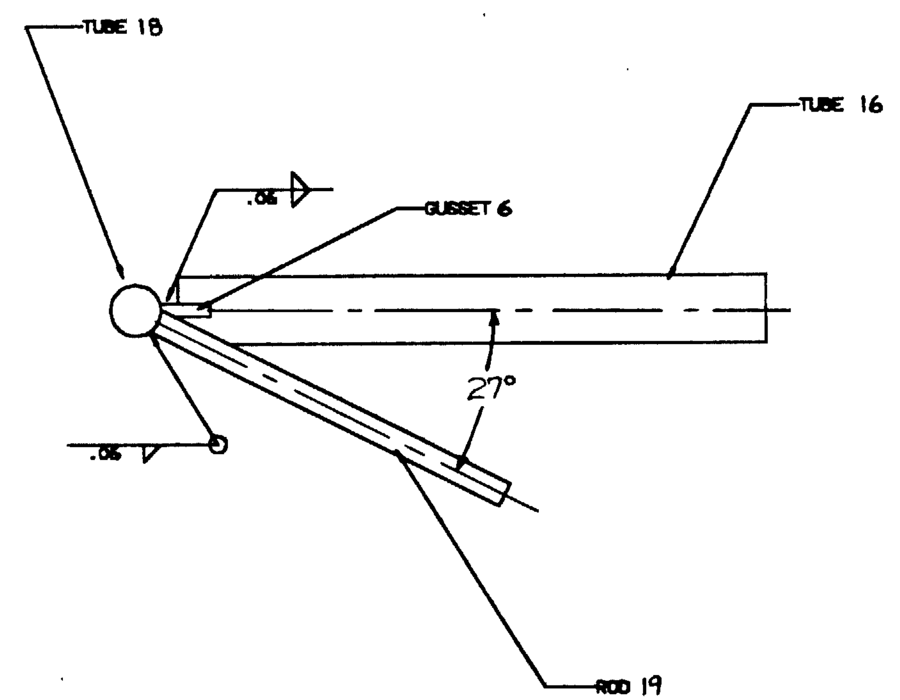


SIDE VIEW

NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM.
2. SCALE =

TIBIA WELDING DETAILS
DWG 9.1
SHT 1 OF 8



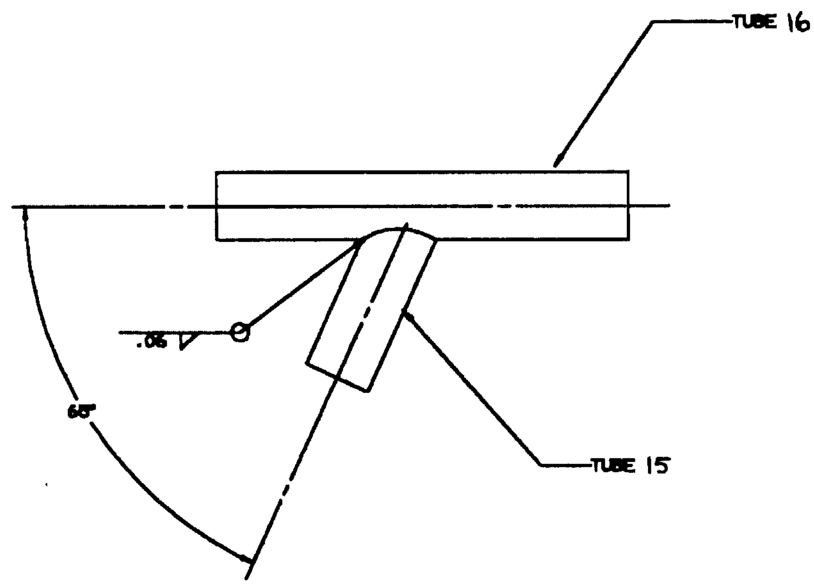
NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

TIBIA WELD

DWG 9.2

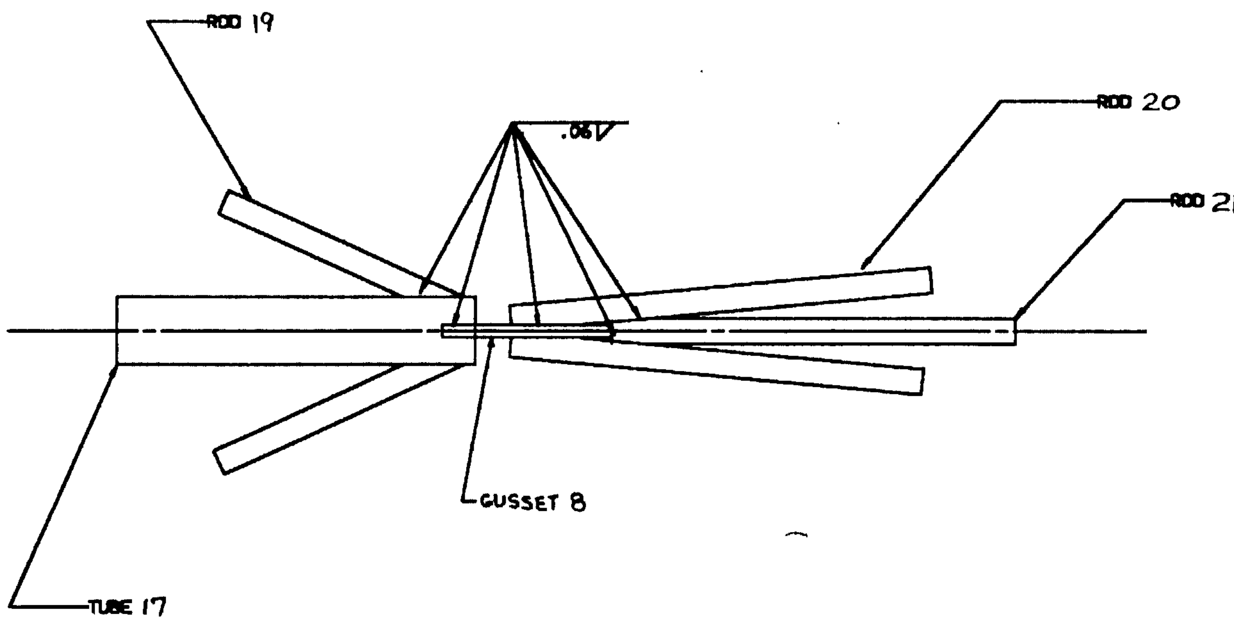
SHT 2 OF 8



NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

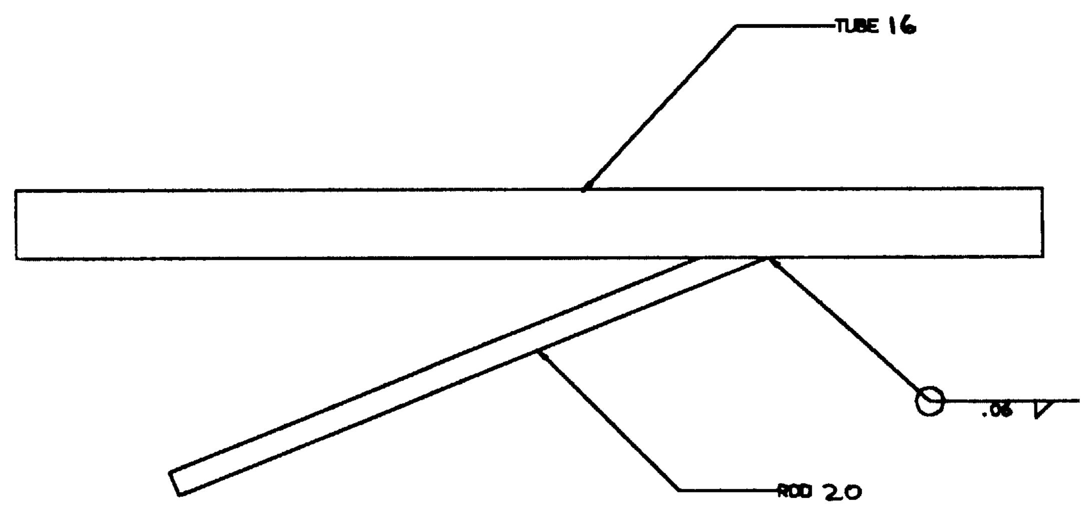
TIBIA WELD
DWG 9.3
SHT 3 OF 8



NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

TIBIA WELD
DWG 9.4
SHT 4 OF 8



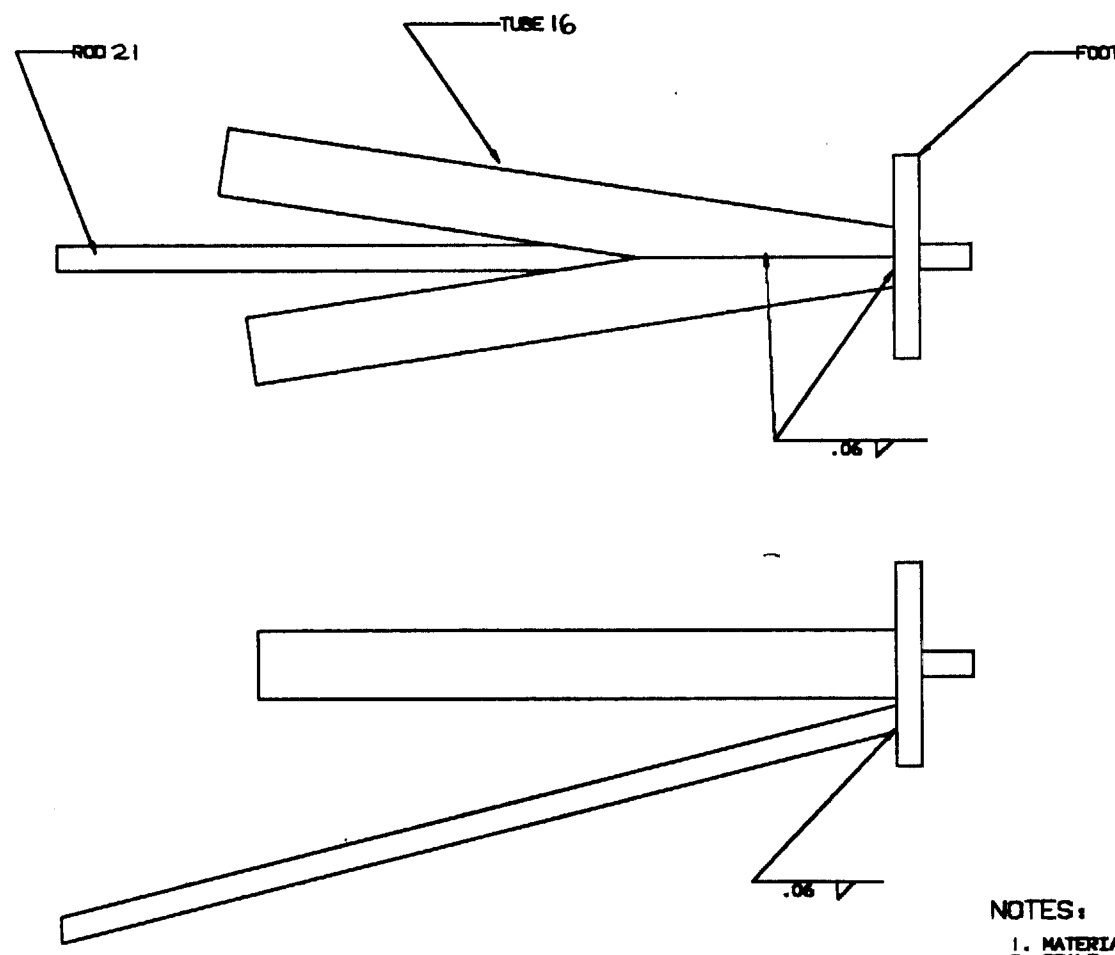
NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

TIBIA WELD

DWG. 9.5

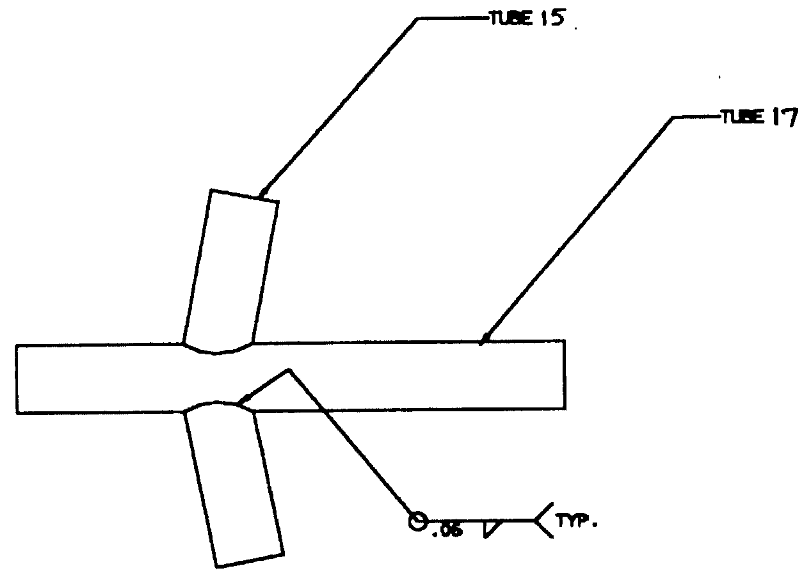
SHT 5 OF 8



NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

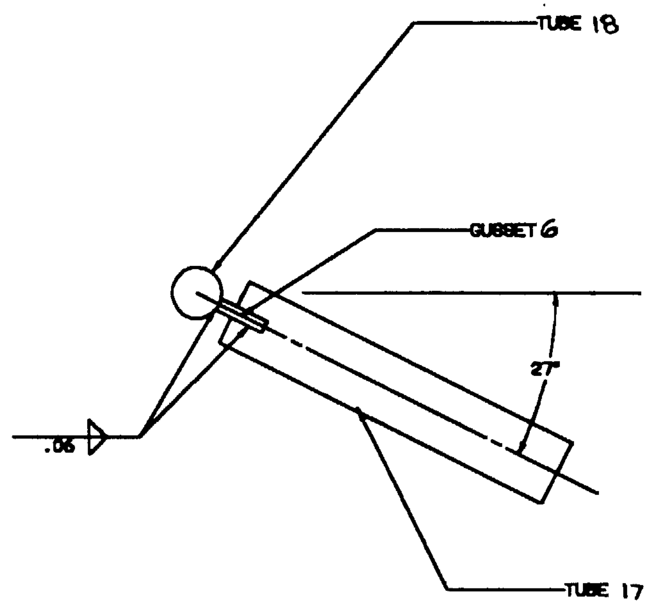
TIBIA WELD
DWG. 9.6
SHT 6 OF 8



NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

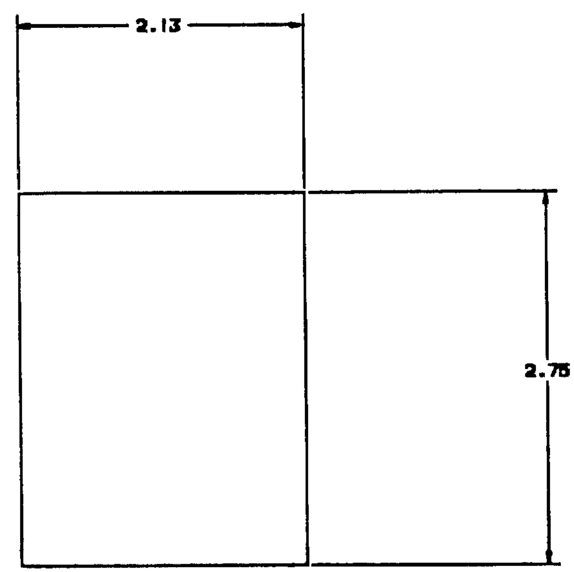
TIBIA WELD
DWG. 9.7
SHT 7 OF 8



NOTES:

1. MATERIAL: 6061-T6 ALUMINUM
2. SCALE = 1X

TIBIA WELD
DWG. 9.8
SHT 8 OF 8



6 REQUIRED

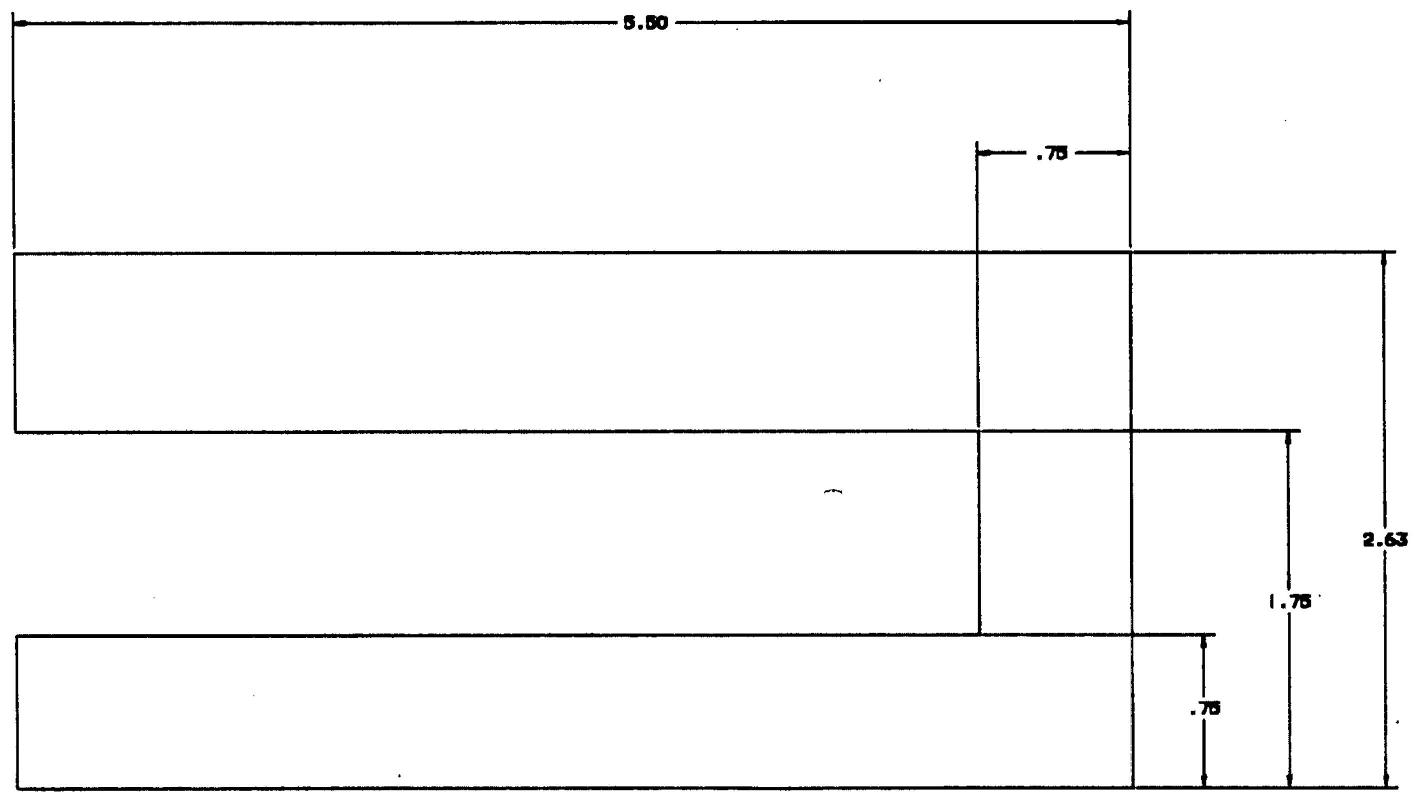
NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM.
2. SCALE = 2X

GUSSET 1

DWG. 10.1

SHT 1 OF 8



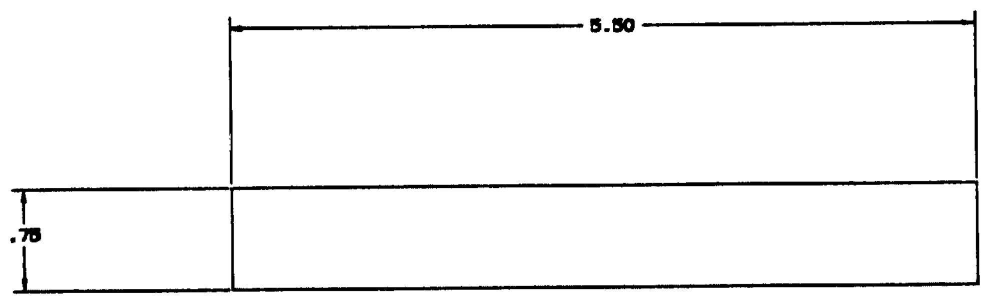
NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM.
2. SCALE = 3X

3 REQUIRED

GUSSET 2
DWG. 10.2
SHT 2 OF 8

3,5

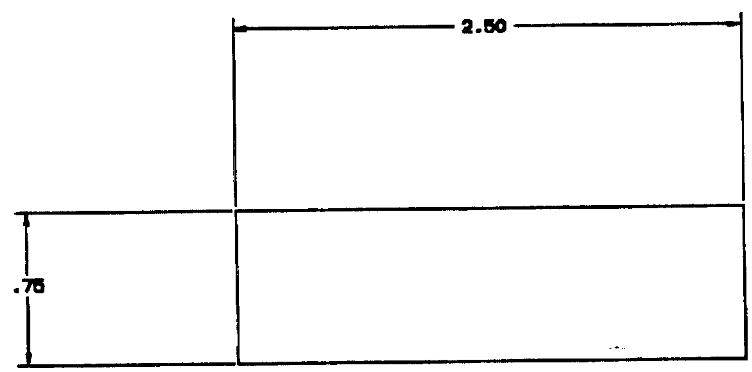


12 REQUIRED

NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM.
2. SCALE = 2X

GUSSET 3
DWG 10.3
SHT 3 OF 8



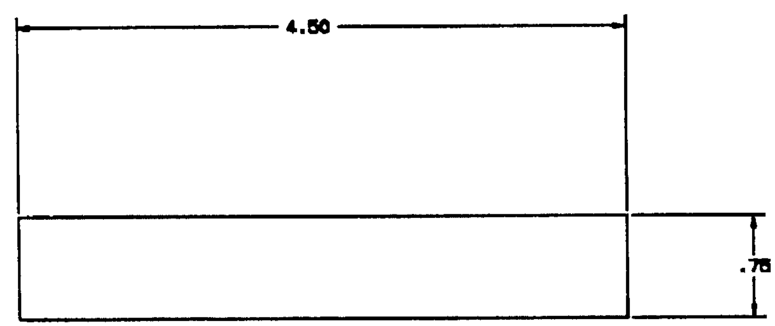
6 REQUIRED

NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM.
2. SCALE = 3X

GUSSET 4
DWG 10.4
SHT 4 OF 8

6

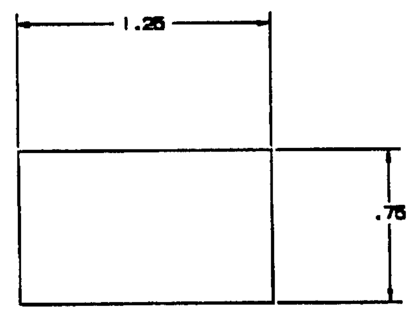


9 REQUIRED

NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM.
2. SCALE = 2X

GUSSET 5
DWG 10.5
SHT 5 OF 8



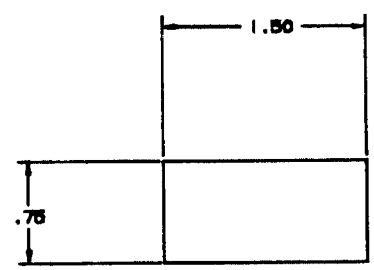
24 REQUIRED

NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM.
2. SCALE = 3X

GUSSET 6
DWG 10.6
SHT 6 OF 8

7

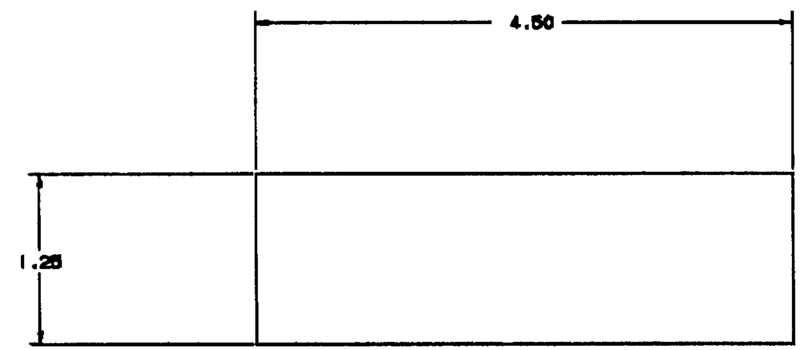


6 REQUIRED

NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM
2. SCALE = 2X

GUSSET 7
DWG 10.7
SHT 7 OF 8



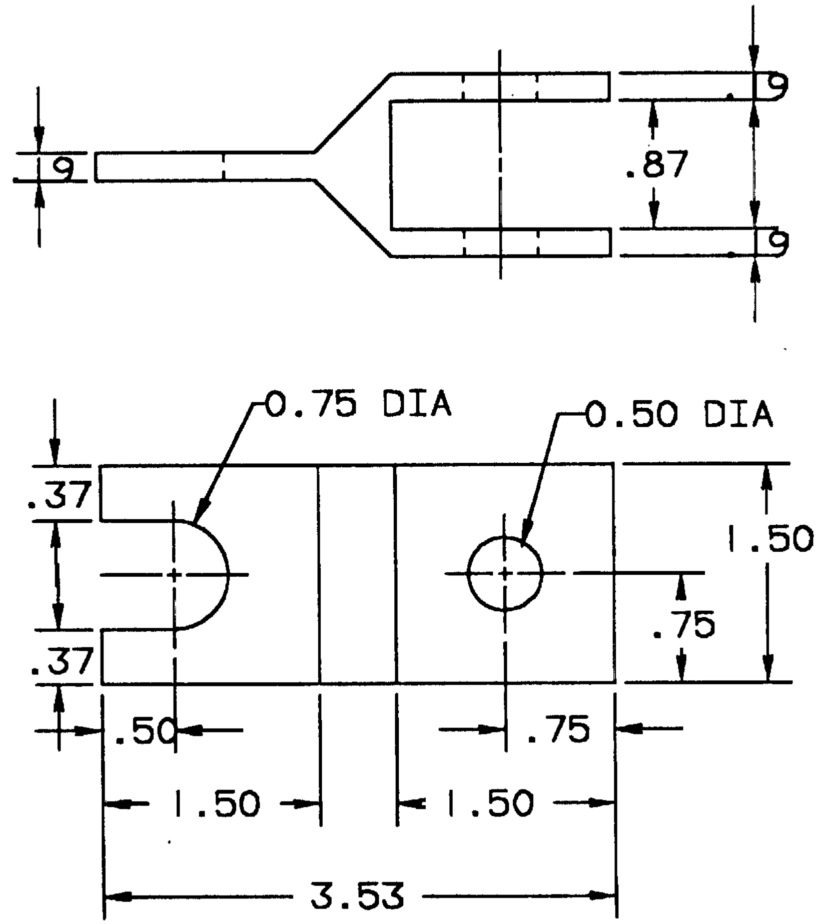
6 REQUIRED

NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM
2. SCALE = 2X

GUSSET 8
DWG 10.8
SHT 8 OF 8

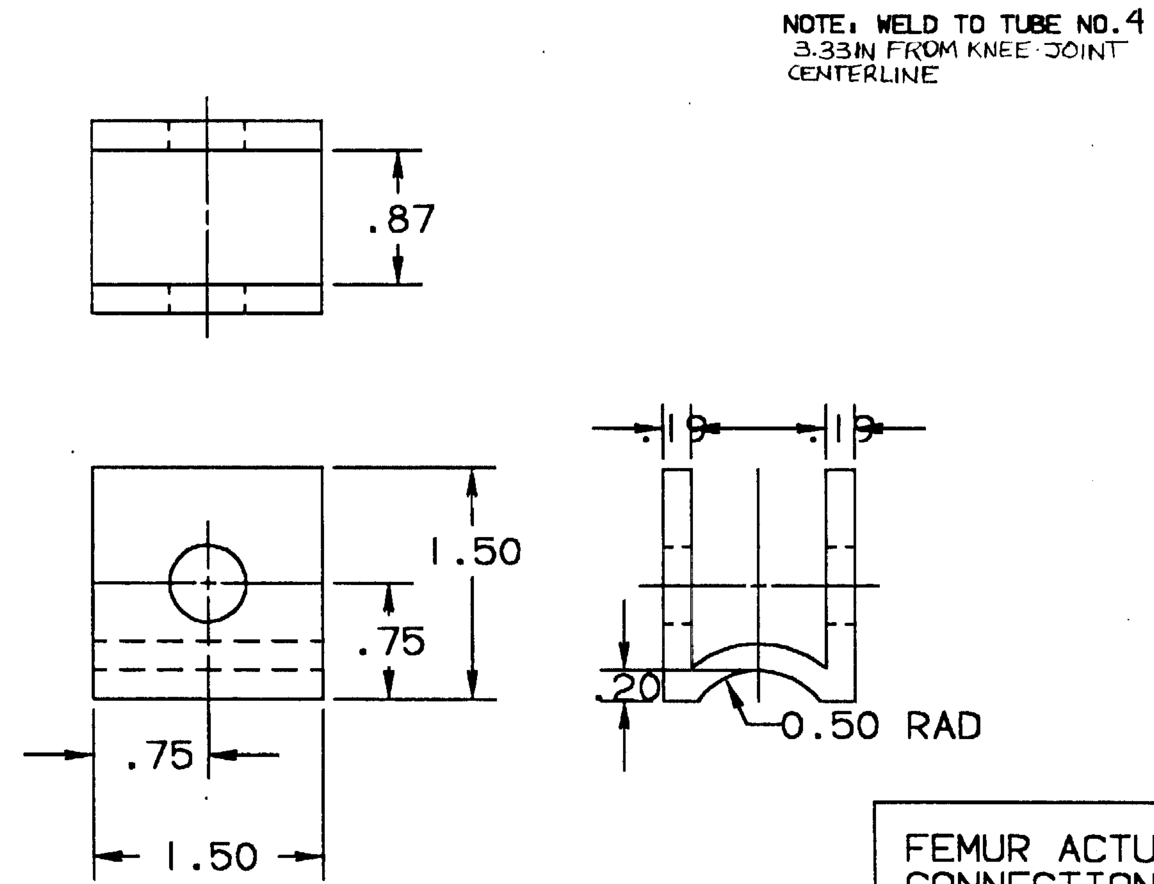
ACTUATOR CONNECTIONS AND LINKAGES



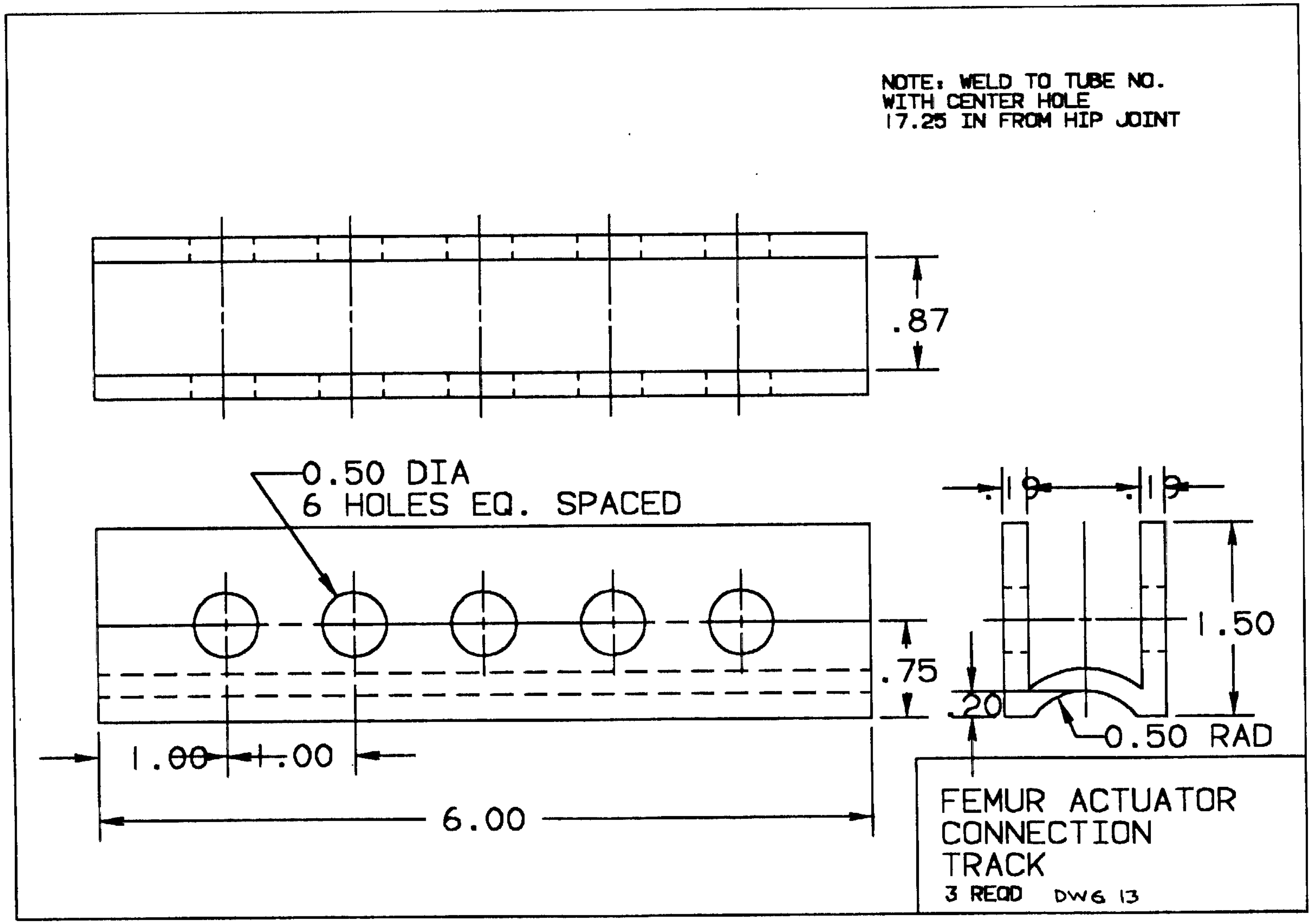
NOTE: WELD TO CONNECT POINTS ON BODY STRUCTURE

BODY ACTUATOR
CONNECTING
GUSSET

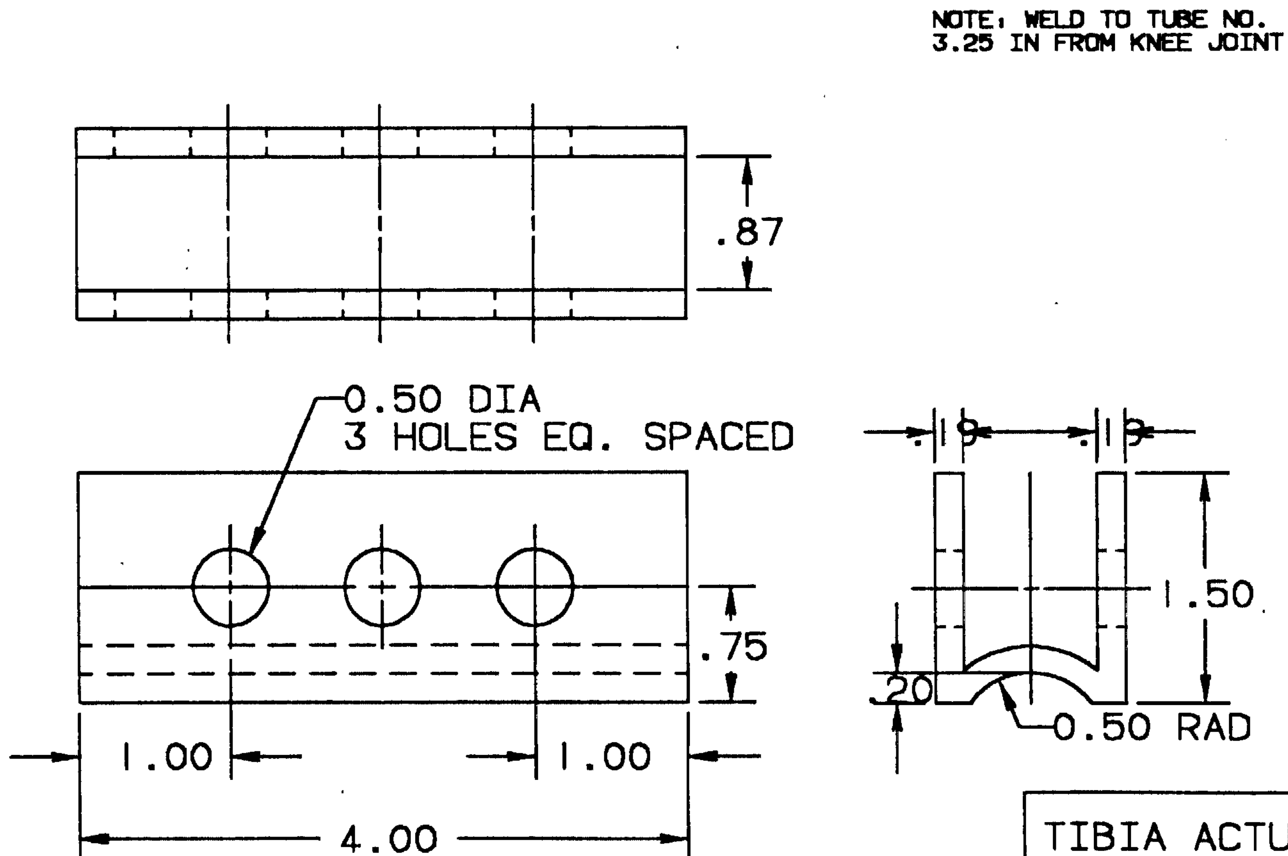
3 REQD DWG 11



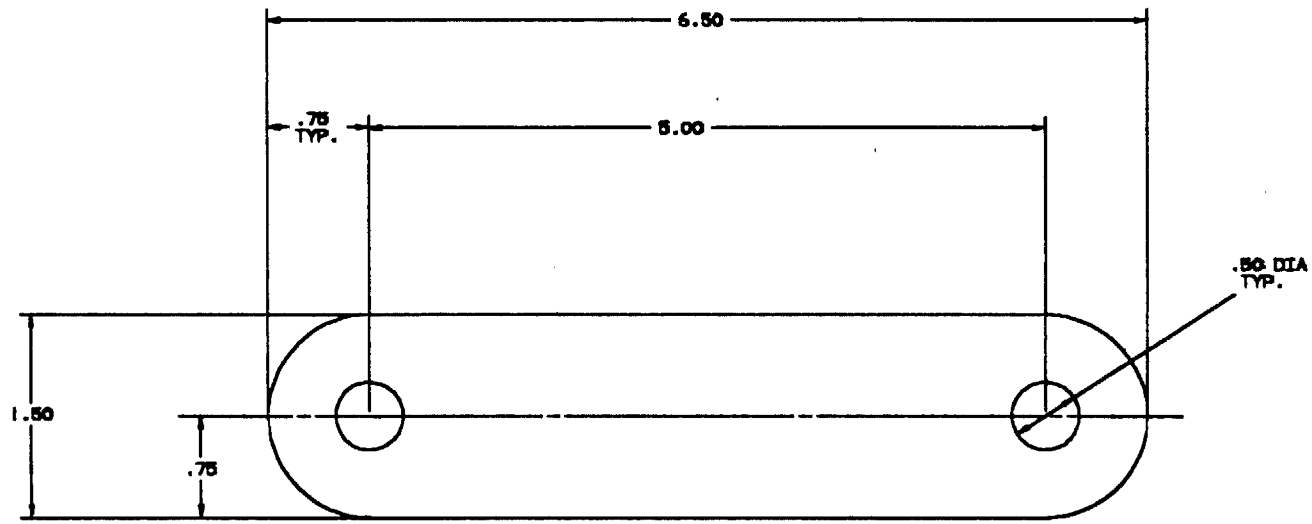
FEMUR ACTUATOR
CONNECTION
BRACKET
DWG 12



NOTE: WELD TO TUBE NO.
WITH CENTER HOLE
17.25 IN FROM HIP JOINT
.87
0.50 DIA
6 HOLES EQ. SPACED
.19
.19
1.50
.75
.20
0.50 RAD
1.00
1.00
6.00
FEMUR ACTUATOR
CONNECTION
TRACK
3 REQD
DWG 13



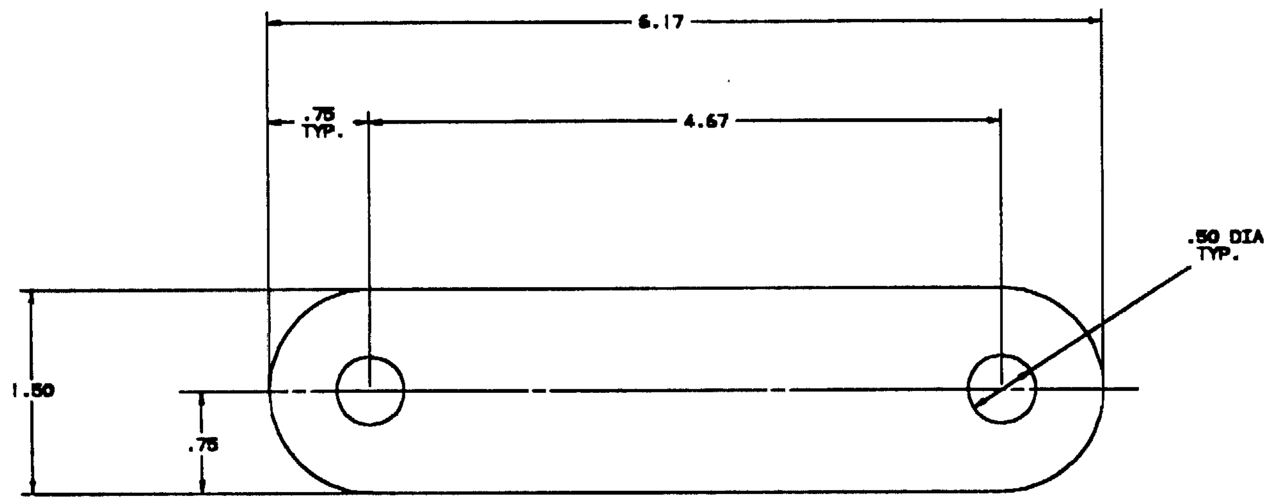
TIBIA ACTUATOR
CONNECTION
TRACK
3 REQD DWG 14



NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM
2. SCALE = 2X

CRANK LINK
DWG 15.1
SHT 1 OF 2



NOTES:

1. MATERIAL: .1875 6061-T6 ALUMINUM
2. SCALE = 2X

COUPLER LINK

DWG. 15.2

SHT 2 OF 2

APPENDIX 1

CALCULATIONS

INTRODUCTION SUPERTAB

1A. TIBIA

1B. FEMUR

1C. BODY

1D. DRIVE TRAIN

Supertab

Supertab is a finite element software package developed by the Structural Design Research Corporation (SDRC) which runs on the Apollo Corporation's DN 560 terminal. It is a menu-driven system which permits the user to create, modify, optimize, and test physical structures for design analysis. Supertab aided significantly in our final design of the Skitter II Tubular Truss Structure. By creating several nodes and elements along the proposed members of the structure and entering the proper physical and material properties of each member, it is possible to obtain an intricate displacement, stress, reaction force, and strain energy analysis of each member of the structure.

The three basic parts of the structure, the body, femur, and tibia, were entered separately into three different files. Each part was analyzed separately, assuming major connections, *i.e.* hip and knee joints were rigid. Nodes and elements were created in high numbers in areas of high stress concentration to insure accurate analysis of the forces at the joints. Three basic sizes of Aluminum 6061 tubing were analyzed in the analysis: these were 3/8", 3/4", and 1" nominal diameter tubes. Each element created in supertab was modeled after the beam geometry to optimize those members in compression, *e.g.* to more closely resemble 2-force member compression locally.

Once structural geometry was completed and all nodes and elements were created, a force analysis was required (Appendix D) by hand to accurately input the five loading conditions. The restraints, as previously mentioned, effect general reactions in the model. With the applied loads and restraints it is possible to run supertab and query for solution.

The analysis obtained by Supertab has allowed optimization of the original design to the point where, even under extreme loading, the structure will not fail. A stress analysis for each part of the structure provided information as to which members in the original structure were necessary or extraneous due to insignificant stress. The displacement analysis also allowed for the visualization of the effect of extreme loading on the proposed structure. Using the information obtained, tube size was increased in areas of high stress.

The ultimate result of the Supertab analysis of the Skitter II Tubular Truss Structure is a structurally sound design for Skitter II that will withstand greater than worst case loading, thus including a built-in factor of safety.

Tibia

FORCE ANALYSIS: ① TIBIA

The force analysis begins with the input load of 150lb at the foot of the tibia. The 150lb force presented here as worst case loading (with tibia in horizontal position) was derived in the program Skit Jump, which maps various motions of Skitter II.

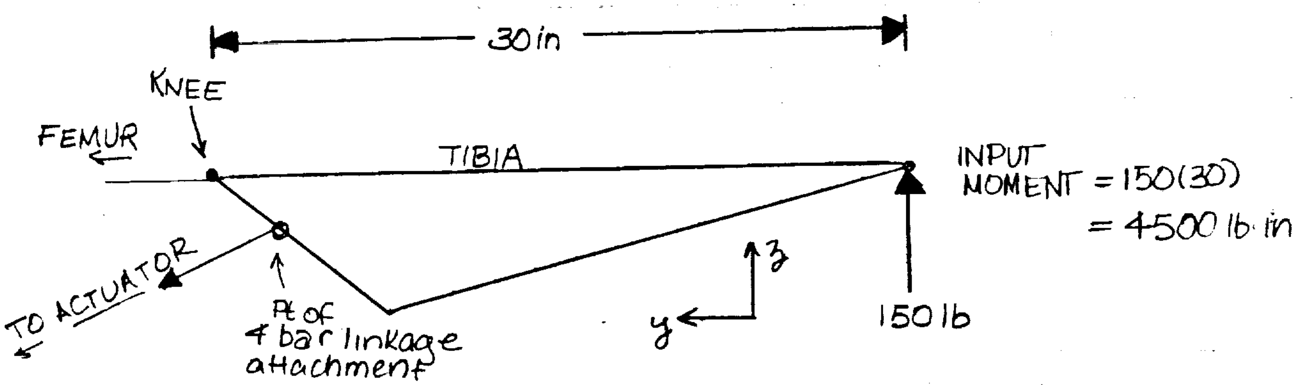


FIG A

With the application of this input load, the tibia will attempt to rotate counterclockwise. In order to hold the tibia flat continuously, the actuator must oppose the input moment of 150 lb (30 in) ← length of tibia or 4500 lb·in. Because the actuator is attached to the tibia by a four-bar linkage, the force applied by the actuator to counteract rotation is not readily apparent. A force analysis at the 4-bar linkage attachment to the tibia now follows in order to obtain an accurate force breakdown at this point. The resultant torque about the knee will still be zero.

FORCE ANALYSIS: TIBIA CONT'D

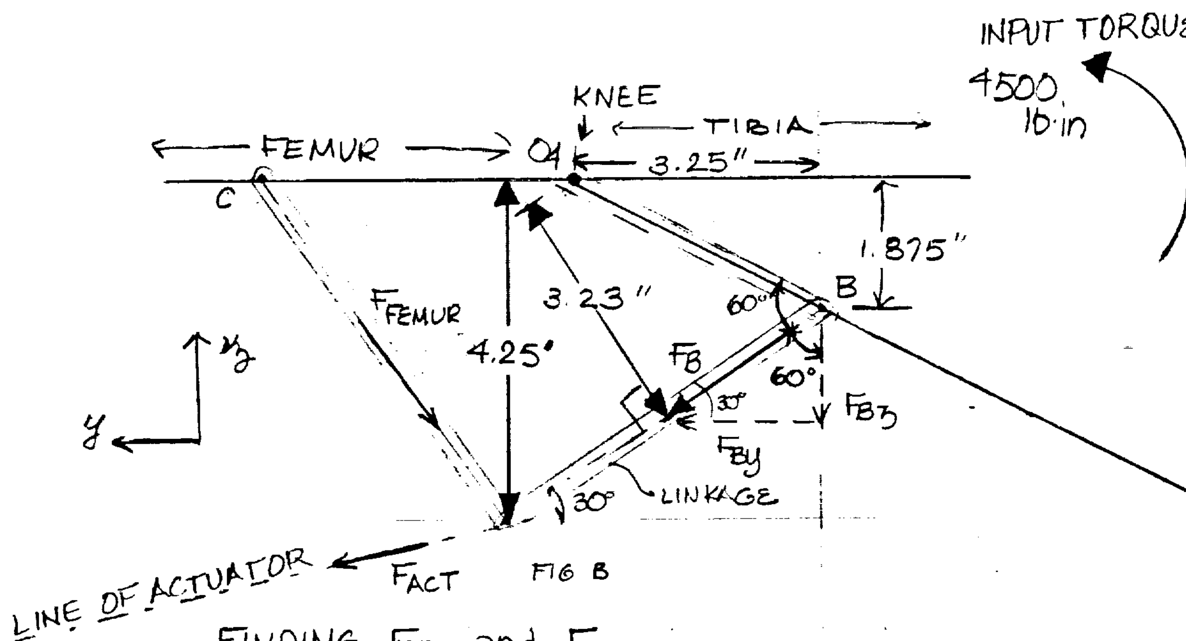


FIG B

FINDING F_{Bz} and F_{By}

The reaction at B can easily be calculated, as F_B (distance to O_4) will exactly equal the input torque of 4500 lb·in:

(5) $$F_B(3.23") = 4500 \text{ lb·in}$$

$$\boxed{F_B = 1393.2 \text{ lb}}$$

TO BREAK F_B UP INTO its y and z components we have:

(6) $$F_{Bz} = (1393.2)\sin 30°$$

$$\boxed{F_{Bz} = 696.6 \text{ lb}}$$

(7) $$F_{By} = (1393.2)\cos 30°$$

$$\boxed{F_{By} = 1206.55 \text{ lb}}$$

THE FINAL FREE BODY DIAGRAM OF THE TIBIA NOW LOOKS LIKE:

FINAL FREE BODY DIAGRAM (TIBIA)

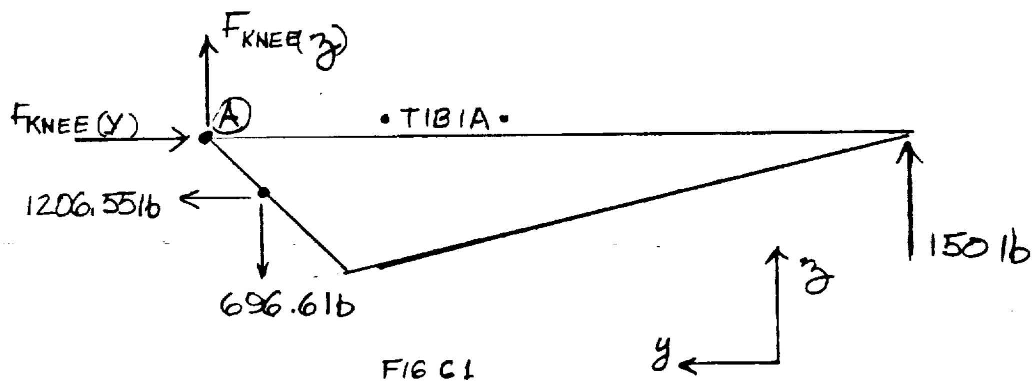


FIG C1

Summation of forces about the knee (A) will give the reaction forces at the knee which can be applied to the femur opposite in direction and equal in magnitude.

(1) $\Sigma F_z = F^*_{KNEE}(z) + 150\text{lb} - 696.6\text{lb} = 0$

$F^*_{KNEE}(z) = 546.6\text{ lb}$

(2) $\Sigma F_y = 1206.55\text{ lb} - F^*_{KNEE}(y) = 0$

$F^*_{KNEE}(y) = 1206.55\text{ lb}$

* Since the tibia connects along a hinge, at two points, to the femur, the point labeled (A) sees only $\frac{1}{2} F^*_{KNEE}(z)$ & $\frac{1}{2} F^*_{KNEE}(y)$ thus

(3) $\boxed{F_{KNEE}(z) = \tfrac{1}{2}(546.6) = 273.3\text{ lb}}$

(4) $\boxed{F_{KNEE}(y) = \tfrac{1}{2}(1206.55\text{lb}) = \ominus 603.275\text{lb}}$

at (A)

TIBIA ANALYSIS

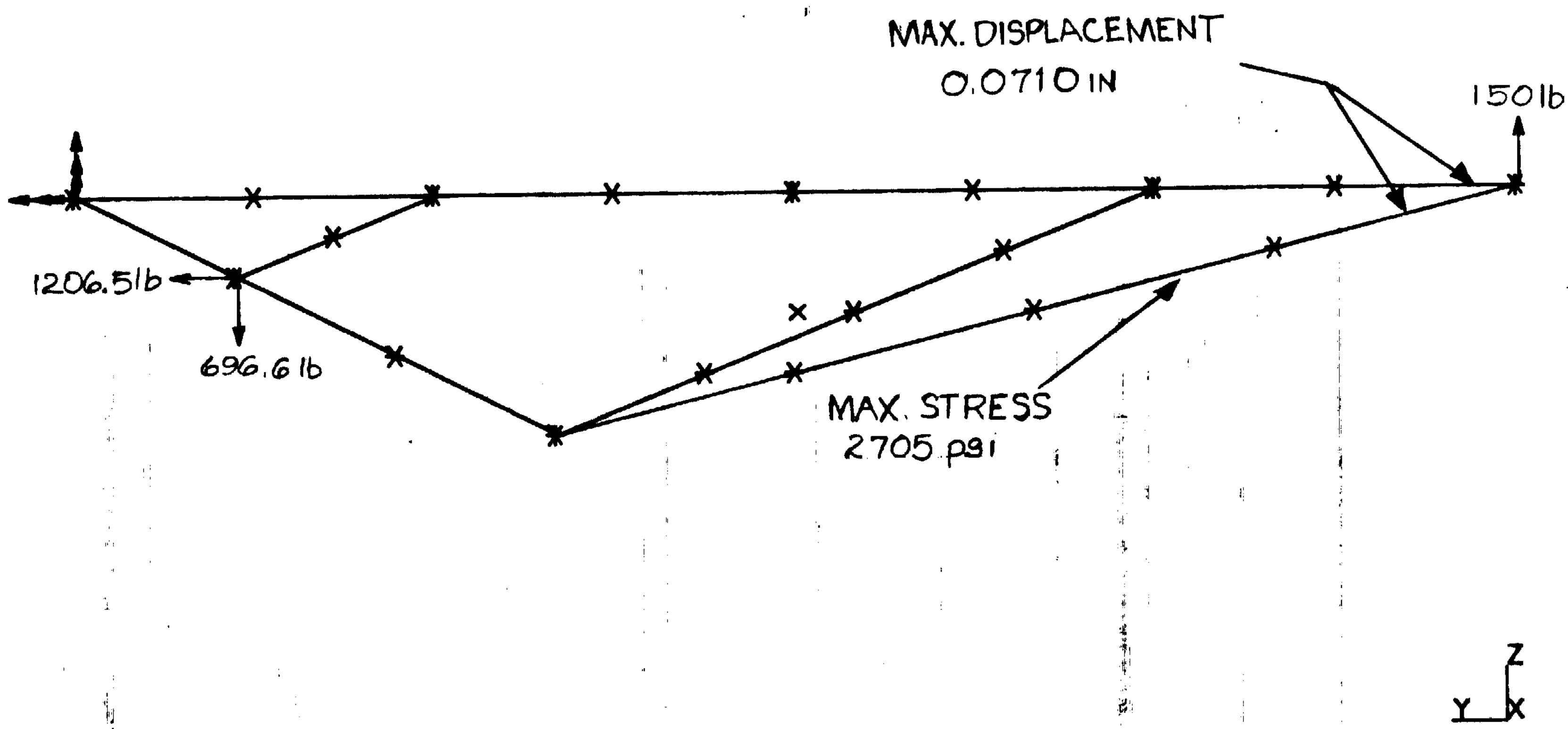


FIGURE C2

FORCE ANALYSIS: TIBIA - ACTUATOR - FEMUR

Before a force analysis can be done on the femur, the actuator force, which ultimately restricts rotation of the tibia must be calculated.

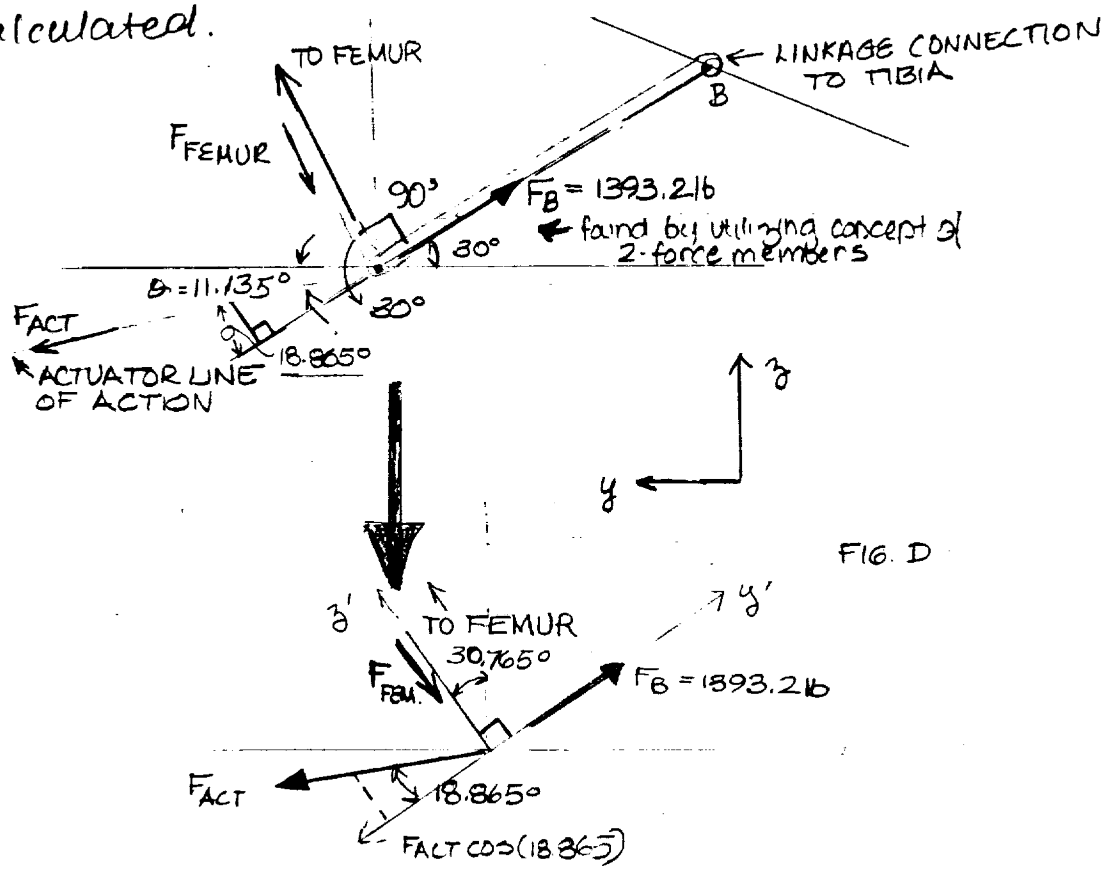


FIG. D

(8) $\Sigma F_{y'} = 0$;

$$F_{ACT}\cos(18.865) = 1393.2\text{ lb}$$

$$\boxed{F_{ACT} = 1472.28\text{ lb}}$$

(9) $\Sigma F_{z'} = 0$ can now be calculated.

$$F_{ACT}(\sin 18.865) = F_{FEMUR}$$ — force along linkage attached to femur

$$F^{*}_{FEMUR} = (1472.28)\sin 18.865$$

$$\boxed{F_{FEMUR} = 476.05\text{ lb}}$$

Femur

Force Analysis : (2) Femur

The force analysis of the femur begins with the reaction forces from the tibia that act at the knee, and the two forces created by the reaction of the actuator, directly (F_{ACT}) and indirectly. (F_{FEMUR})

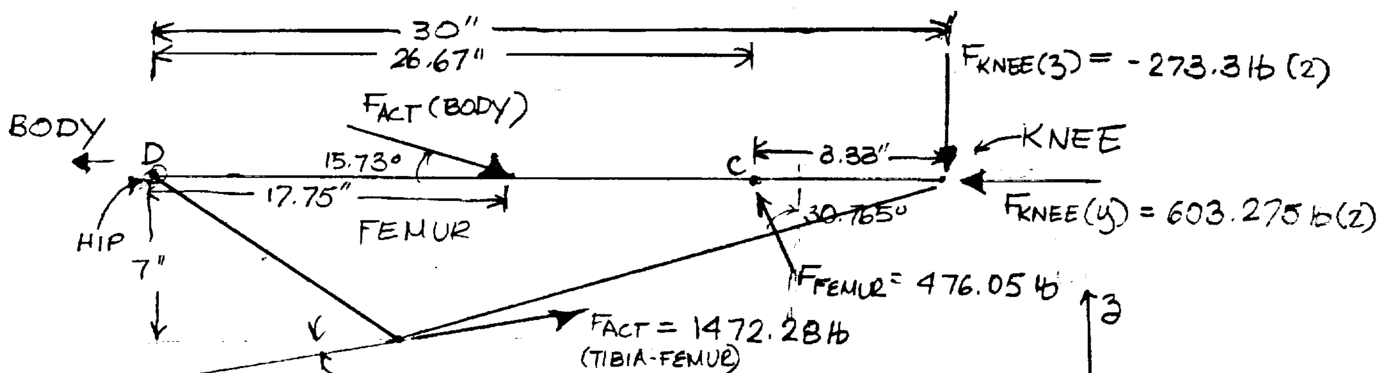


FIG E

The second actuator now comes into play (body-femur) to insure that the femur doesn't rotate out of the horizontal X-y plane. For this condition to be satisfied, the summation of moments about the hip, point D, must be zero (Ø).

Summation of Torques about D follows

(10)

$$\circlearrowleft + \sum M_D = 0 = F_{ACT(BODY)} \sin(15.73)(17.75") + (273.3)(2)(30) - (476.05)(\cos 30.765)(26.67")$$
$$- 1472.28(\cos 11.135)(7") = 0$$

$$\boxed{F_{ACT}(BODY) = 960.75 \text{ lb}}$$

(11) $F_{ACT}(BODY)_z = (960.75)(\sin 15.73) = (-)\ 260.465$ lb

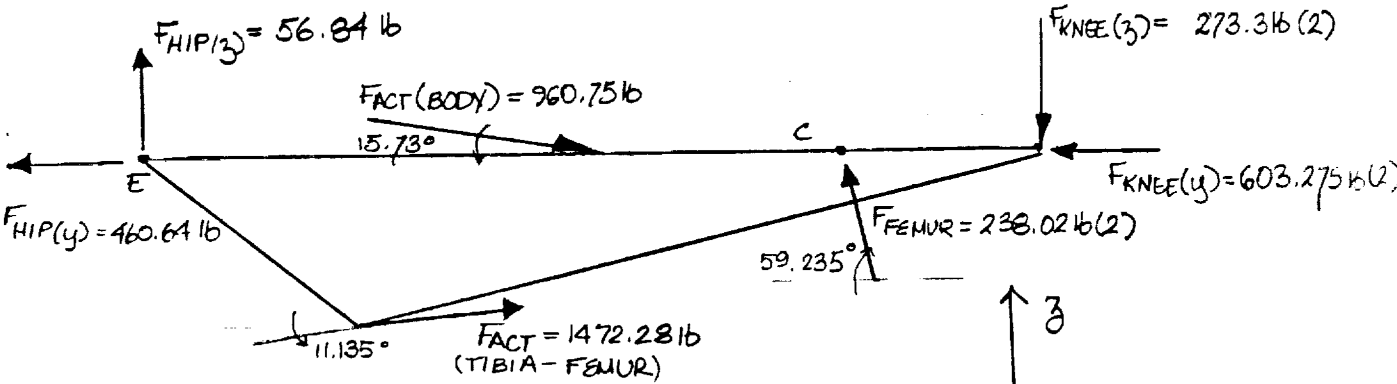
$$\boxed{F_{ACT}(BODY)_z = -260.465 \text{ lb}}$$

(12) $F_{ACT}(BODY)_y = (960.75)(\cos 15.73) = (-)\ 924.77$ lb

$$\boxed{F_{ACT}(BODY)_y = -924.77 \text{ lb}}$$

FORCE ANALYSIS: FEMUR (cont'd)

A FINAL FREE BODY DIAGRAM FOR THE FEMUR CAN NOW BE DRAWN AND THE REACTION FORCES AT THE HIP CAN BE DETERMINED.



AT E FIG E1

(13) $\Sigma F_z = 0$;

$$F^*_{HIP(z)} + 238.02(2)\sin 59.235 + 1472.28(\sin 11.135) - 960.75(\sin 15.73) - 273.3(2) = 0$$

$$F^*_{HIP(z)} = {}^{+}113.68 \text{ lb}$$

(14) $\Sigma F_y = 0$;

$$F^*_{HIP(y)} + 238.02(2)\cos 59.235 + 603.275(2) - 1472.28(\cos 11.135) - 960.75(\cos 15.73) = 0$$

$$F^*_{HIP(y)} = {}^{+}919.28 \text{ lb}$$

AGAIN, SINCE the hip is attached along the hinge at two points, the reaction at each joint is half of F_{HIP}^*; ie

(15) $\boxed{F_{HIP(z)} = 1/2\,(113.68) = 56.84 \text{ lb}}$

(16) $\boxed{F_{HIP(y)} = 1/2\,(919.28) = 460.64 \text{ lb}}$

ALL THE NECESSARY FORCES HAVE BEEN CALCULATED TO DETERMINE THE FREE BODY DIAGRAM FOR THE BODY

FEMUR ANALYSIS

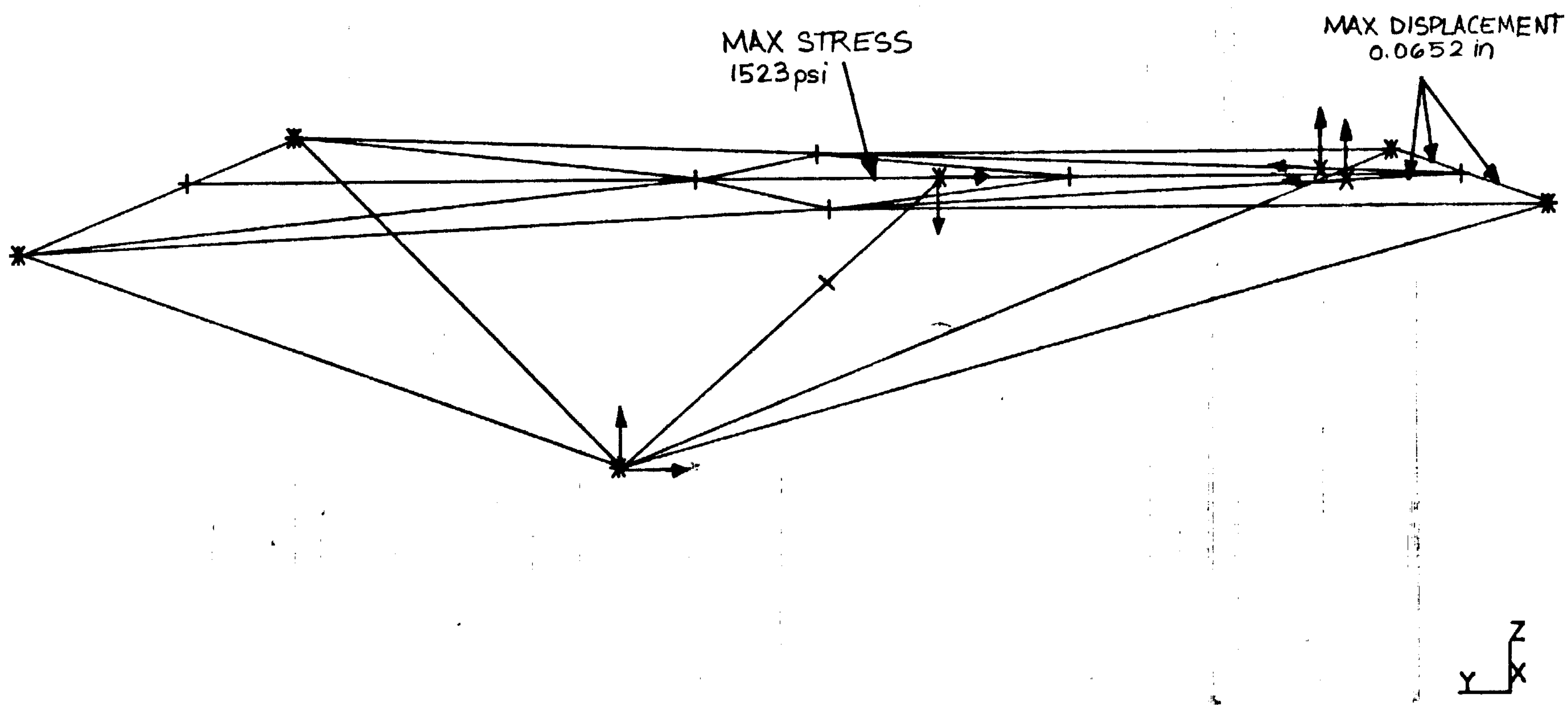


FIGURE F2

Body

FORCE ANALYSIS: ③ BODY

THE DIAGRAM BELOW DEPICTS THE RESULTANT FORCES ACTING ON 1/3 OF THE BODY WHEN LOADED UNDER WORST CASE CONDITIONS (ie. 150lb input at foot)

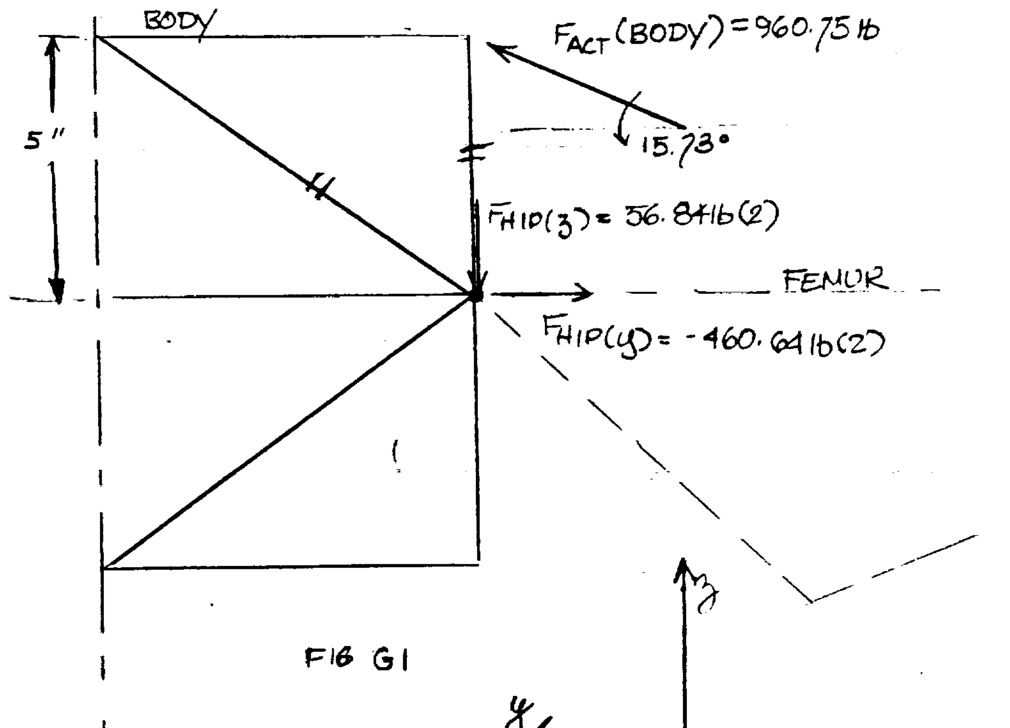


FIG G1

BODY CENTER LINE

ANALYSIS OF THE WHOLE BODY CAN BE ACCOMPLISHED BY APPLYING THE ABOVE FORCES AT 120° ROTATIONS FROM ABOVE VIEW. AFTER CAREFUL TESTING ON SUPERTAB IT WAS ESTABLISHED THAT UNDER THE ABOVE (x 3) CONDITIONS, THE BODY'S MAXIMUM DEFLECTION WAS ONLY $6.38(10^{-3})$ in AND OCCURS IN THE MEMBER(S) MARKED WITH "//".

TOTAL DEFLECTION = 0.0067" + 0.0652" + 0.077"
(at worst case loading) = 0.1489 in
(at body → down to tibia)

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BODY ANALYSIS

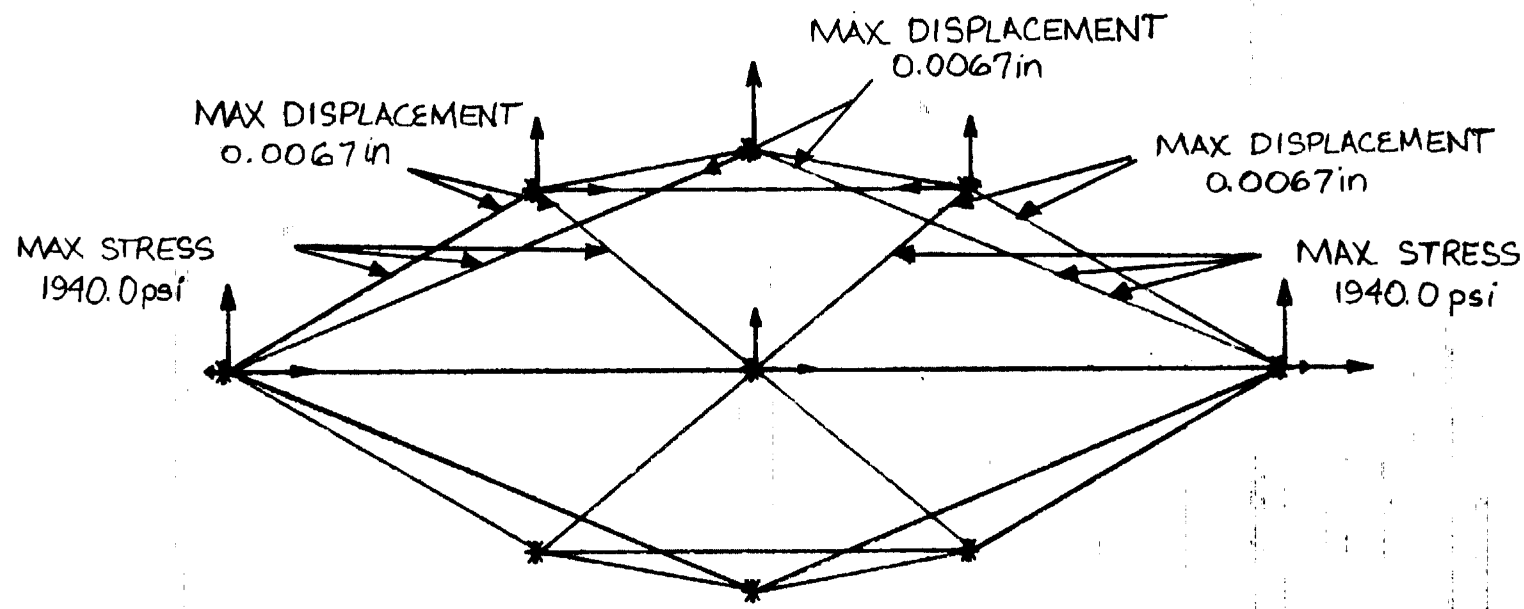


FIGURE G2

Drivetrain

Appendix 1D Drivetrain Design

Location of Body - Femur Actuator

The actuator was located by placing it with half of its stroke length between the body and the femur with the femur in a horizontal position. The attach point on the femur was then moved farther away and closer to the body in order to optimize the range of motion available with the given actuator (14 inches dead length with an 8 inch stroke) without employing a four - bar linkage or some other device to create even more extended motion (Figure 1).

Additionally, the actuator can produce 1500 lbs. of force. The actuator force was checked in the leg's worst case positioning scheme to check its capabilities. The force required was well within the actuator's capabilities (see Appendix1d).

Design of Knee Joint Drivetrain

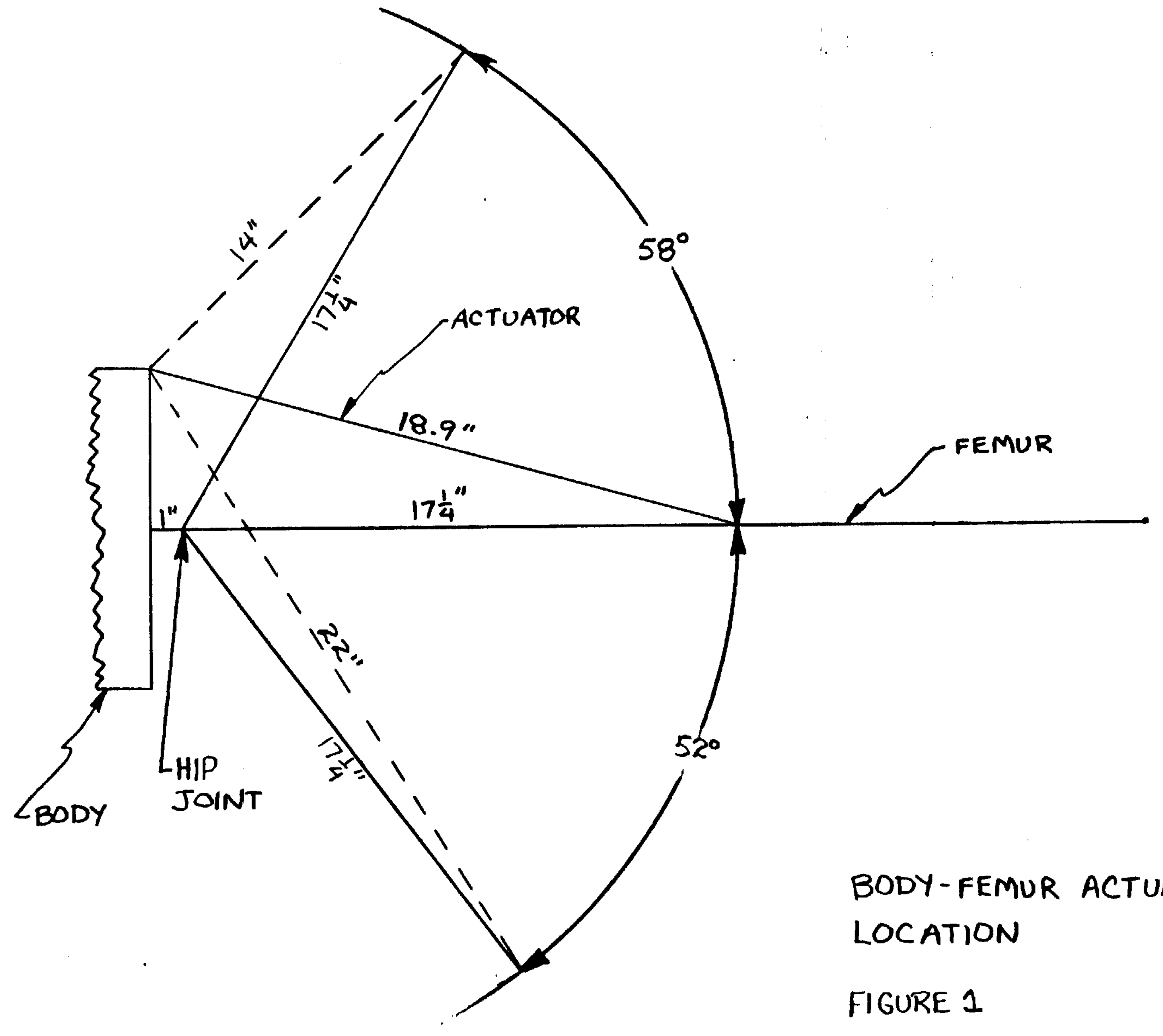
The actuators specified for Skitter II have an eight inch stroke. The 4-bar linkage used at the knee joint must be capable of converting this input into 180 degrees of rotation. Therefore, the actuator connection points on the extreme positions of the crank must not be more than eight inches apart.

A drawing was made of the 4-bar linkage in its extreme positions. It was drawn with the links proportional to those of a rotational mechanism on a backhoe bucket (Figure 2). The distance between the actuator connection points was then measured. The length was then converted to eight inches and the lengths of the links were adjusted by the same factor.

Next, another drawing was made of the linkage in its extreme positions as well as the mid-way position. The line of action of the actuators at each position was also drawn (Figure 3). From this drawing the actuator connection point on the femur was determined. Many angles useful in the force analysis of the linkage were determined from this drawing also.

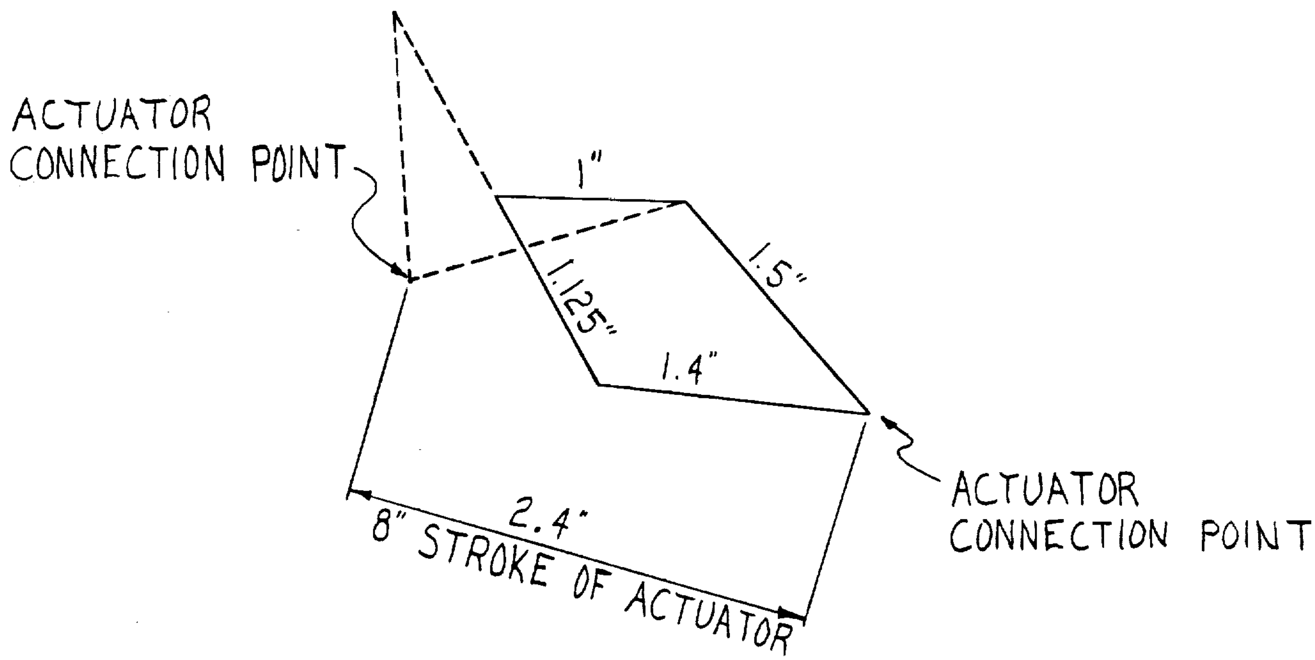
After the position analysis, a force analysis was performed. The specified actuators for Skitter II are capable of producing up to 1500 lb. force. The 1500 lb. input to the 4-bar linkage must be capable of creating a 4500 in-lb moment on the tibia about the knee joint. This moment is the maximum moment required to move the tibia. The force analysis of the 4-bar linkage began with a free body diagram of the tibia (Figure 4). From this diagram the force in the coupler link was found. With this force the force required by the actuator was found by summing moments about the crank pivot point. The force required by the actuator was found to be less than 1500 lb. Therefore, the 4-bar linkage is capable of creating the required moment.

Finally, a critical load analysis was performed to find the required size of the crank and coupler links. The height of the links was determined by the pin hole size required at the link connection points. Once the height and critical load were determined, we were able to calculate the appropriate link thickness (Figure 5).



BODY-FEMUR ACTUATOR LOCATION

FIGURE 1



2.4 in MUST BE CONVERTED TO EQUAL 8 in STROKE OF THE ACTUATOR. THE CONVERSION FACTOR IS $8/2.4 = 3.33$.

STATIONARY LINK = 1" x 3.33 = 3.33"
CRANK LINK = 5"
COUPLER LINK = 4.67"
FOLLOWER LINK = 3.75"
ACTUATOR STROKE = 8"
ACTUATOR CLOSED = 14"
ACTUATOR OPEN = 22"

FIGURE 2

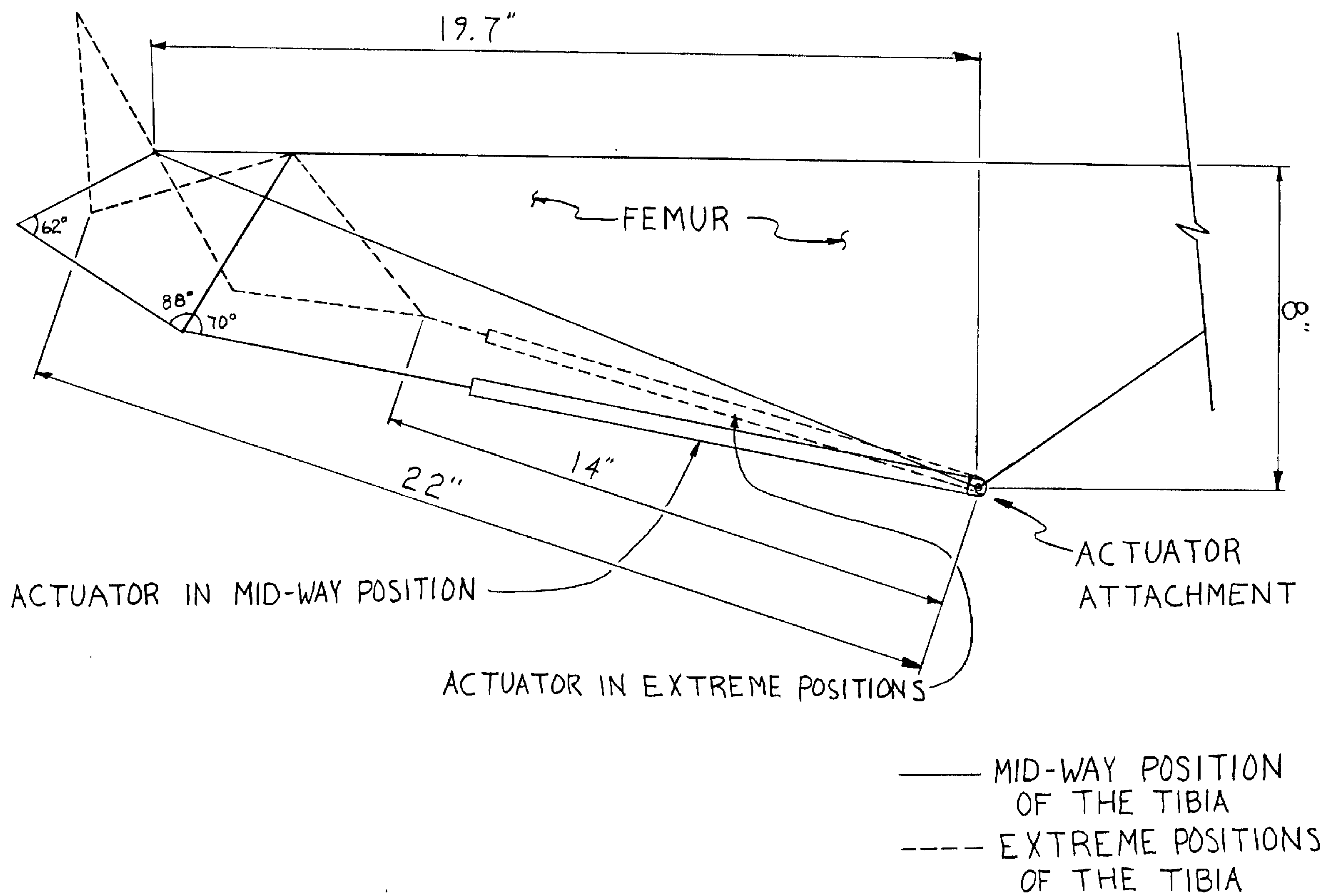
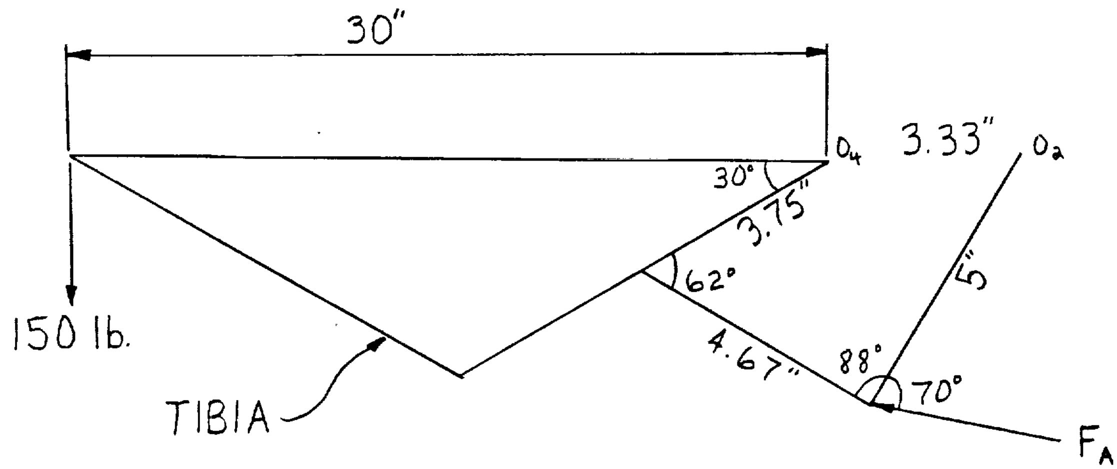
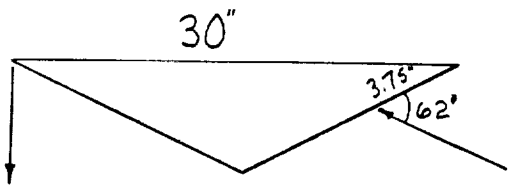

19.7"
8"
FEMUR
62°
88°
70°
22"
14"
ACTUATOR ATTACHMENT
ACTUATOR IN MID-WAY POSITION
ACTUATOR IN EXTREME POSITIONS
MID-WAY POSITION OF THE TIBIA
EXTREME POSITIONS OF THE TIBIA

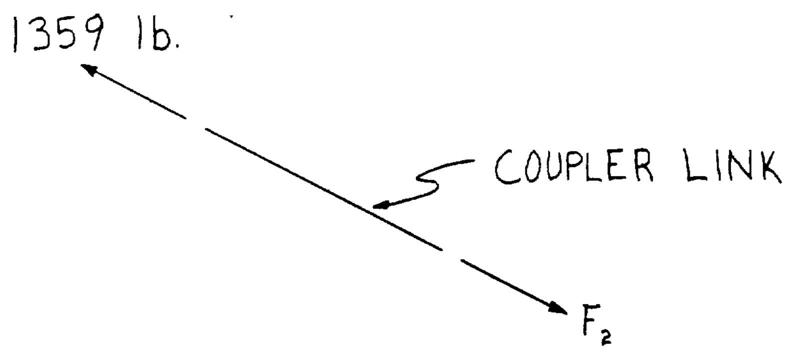
FIGURE 3



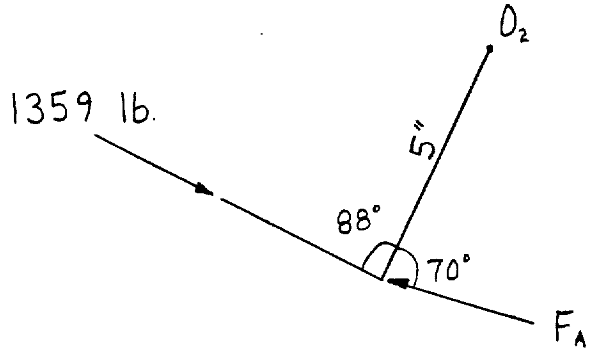


M_{O_4}: $(150\text{ lb.})(30\text{ in}) - (3.75\text{ in})F_1 \sin 62° = 0$

$F_1 = 1359\text{ lb.}$



$F_2 = 1359\text{ lb.}$



M_{O_2}: $(1359\text{ lb})(5\text{ in}) \sin 88° - F_A(5\text{ in}) \sin 70° = 0$

$F_A = 1445\text{ lb.}$

FIGURE 4

$\ell = 5 \text{ in}$

$h = 1.5 \text{ in}$

$P = 1500 \text{ lb}$

$n = 2$

$C = 1$

$E = 10.3 \times 10^6 \text{ psi}$

$S_y = 33 \times 10^3 \text{ psi}$

$$n = \frac{P_{cr}}{P}$$

$$P_{cr} = nP$$

$$P_{cr} = 2(1500 \text{ lb})$$

$$P_{cr} = 3000 \text{ lb}$$

$$I = \frac{P_{cr}\ell^2}{C\pi^2 E} \qquad I = \frac{bh^3}{12}$$

$$\frac{P_{cr}\ell^2}{C\pi^2 E} \leq \frac{bh^3}{12}$$

$$\frac{12 P_{cr}\ell^2}{C\pi^2 E h^3} \leq b$$

$$\frac{12(3000 \text{ lb})(5 \text{ in})^2}{(1)(\pi)^2(10.3 \times 10^6 \frac{\text{lb}}{\text{in}^2})(1.5 \text{ in})^3} \leq b$$

$$b \geq .0026 \text{ in}$$

FIGURE 5

APPENDIX 2

ALTERNATIVE DESIGNS

2A: BODY

2B: STRUCTURES

2C: LINKAGES

2D: ACTUATORS

2E: JOINTS AND CONNECTIONS

2F: MATERIAL SELECTION

Alternative Design for Body Structure

The original triangular body structure is similiar to the final structure which was used for the SKITTER II. Figure 2A shows the first triangular design.

Although this design satisfied the condition of low weight, the configuration was found to be structurally unstable when subjected to lateral forces. This instability can be explained by the fact that the pyramid panels are designed of four-bar configurations and not triangles.

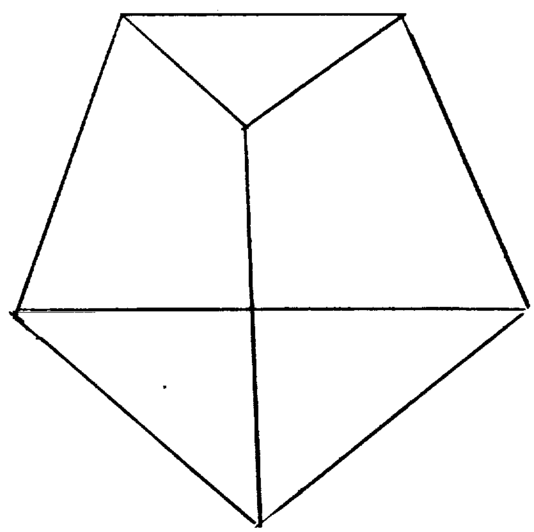


FIG 2A

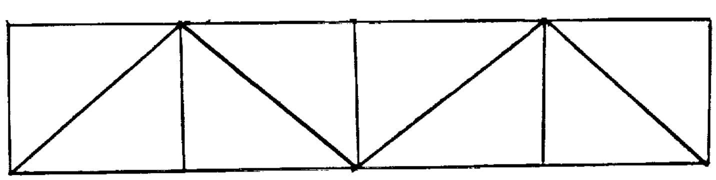
Alternative Design for Structure

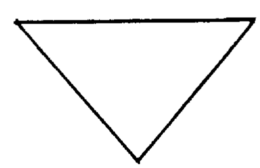
In order to alleviate problems encountered with the welding of the present structure, which is based on the tetrahedron, a triangular geometry could be more easily braced, although creating four - bar geometry on its side planes. These structures would be for the legs.

Another possibility to ease the welding complication would be to employ less efficient shear panels in places where current lateral tube bracing is used.

An additional structure change could be in the choice of material. Instead of the current large size aluminum tube, which requires a massive weld, a smaller, stiffer tube could be employed although actual tube weight could be increased.

Although there exist many possibilities for welding, the procedure chosen should be easier and there should be less weight associated with the weld solutions.





Alternative Design for Knee Joint Power System

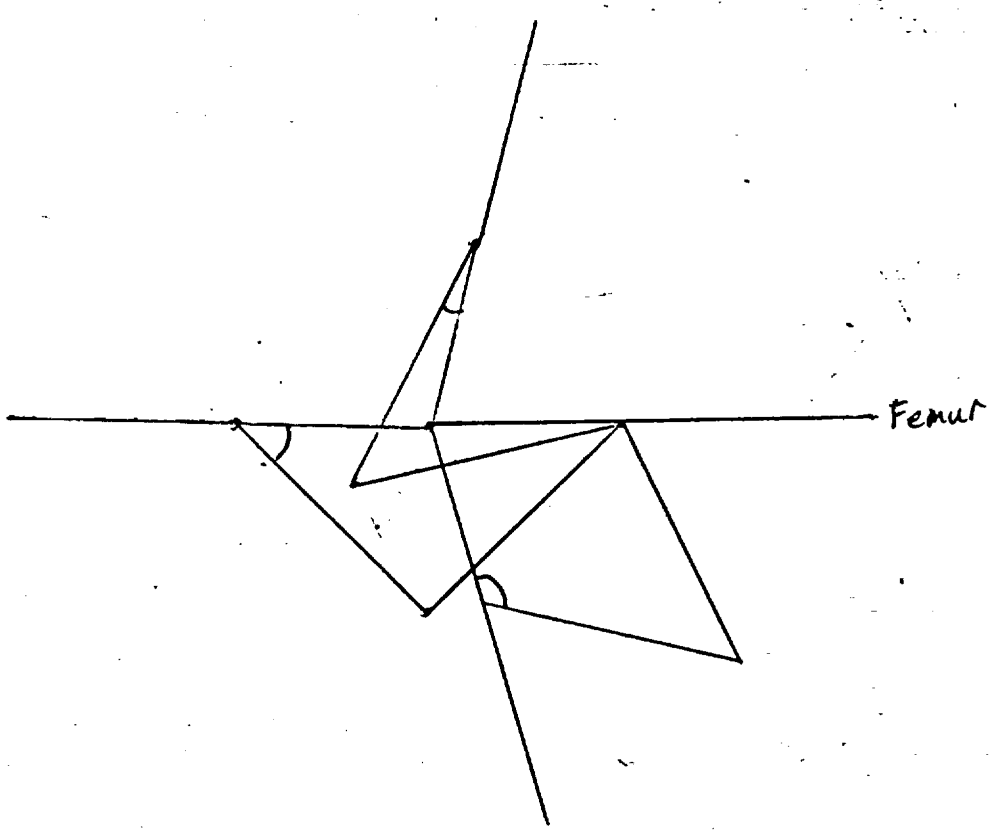
Chain and Sprocket

Many mechanisms were evaluated for powering leg movements at the knee joint. The first was a chain and sprocket system that would convert the linear input at a chain to rotary output at a sprocket. This system would probably work. However, there will be problems with connecting the actuator to the chain. In addition, there are many parts involved making the mechanism both heavy and prone to malfunction.

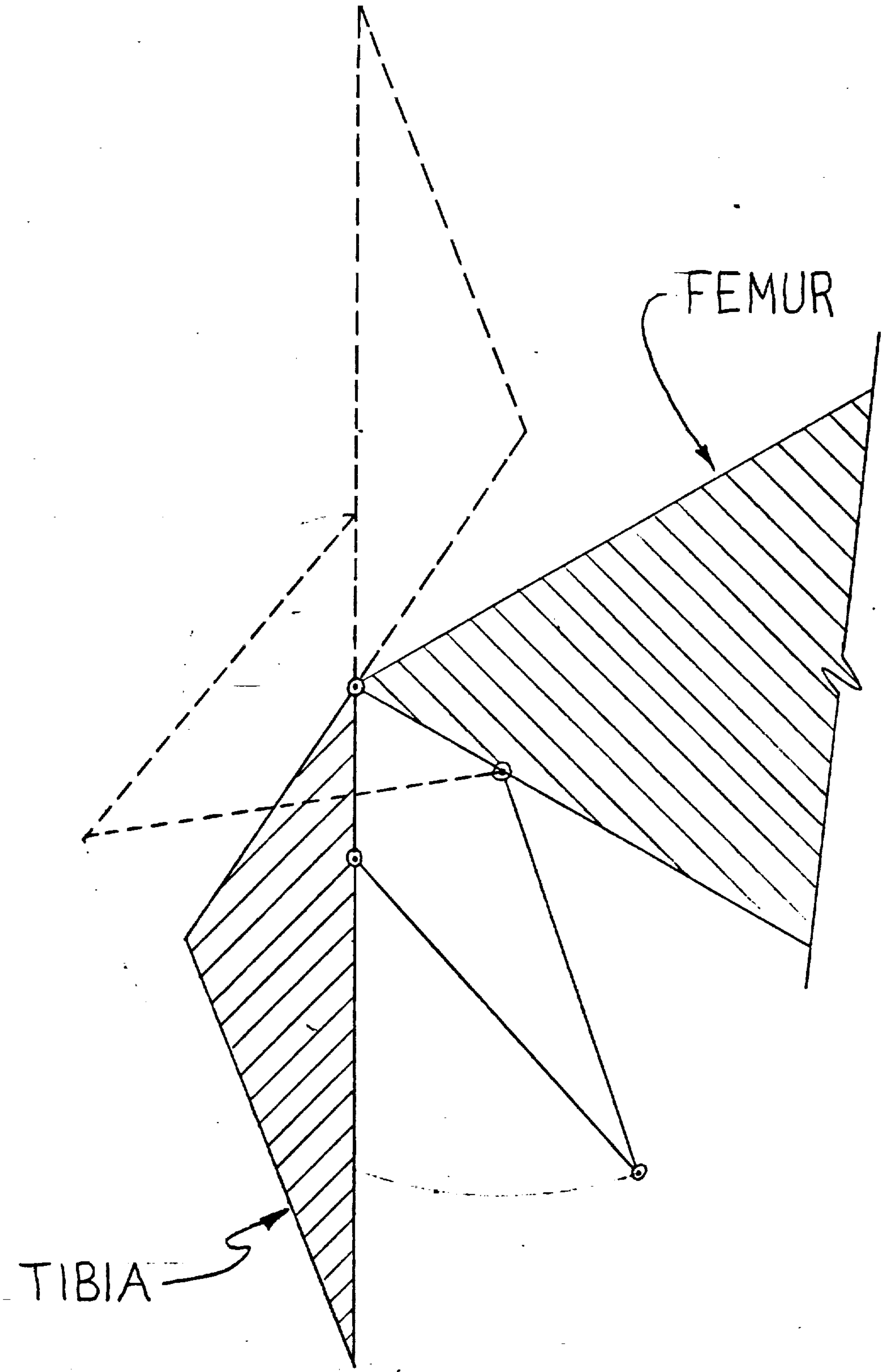
Alternative Design for Knee Joint Power System

Four - Bar Linkages

Several existing four - bar linkages were analyzed that had ranges of rotational output similiar to the range needed at the knee joint. These linkages included the steering mechanism of a pan and the rotational mechanism of several back hoe buckets. These mechanisms did not work because they could not meet torque requirements with the input of the specified actuators.



STEERING MECHANISM
OF A PAN
FIGURE 2C1



FEMUR-TIBIA LINKAGE

FIGURE 2C2

Alternative Design of the Actuators

Two of the problems associated with the four-bar linkage at the knee joint (between the femur and the tibia) are: limited range of motion and an inefficiency in power delivery when the tibia is at the extreme positions.

In this alternative design , the tibia is replaced by actuator A (Figure29). Replacing the tibia by the double sided actuator A , the need for a large range of motion is eliminated and an efficient power delivery is maintained.

The actuator A is connected to the femur, ABF, at the pivot point, B. The link C-D which connects between the body and the actuator creates a 4-bar linkage, ABCD.

At normal operations, the angle between actuator A and the ground is close to 90 º. Therefore, most of the power is used to lower or raise the body.

Actuator B is governing the position of the femur relative to the body changing the position of the femur. The angle between actuator A and the femur also changes. As a result, the position of the body remains the same whereas the position of the tip of actuator A is changed (distance L). This change in location L in conjunction with the change in the length H can be used to create a "walking" motion.

This arrangement of actuator A can be used for walking up-side down as can be seen from Figure .

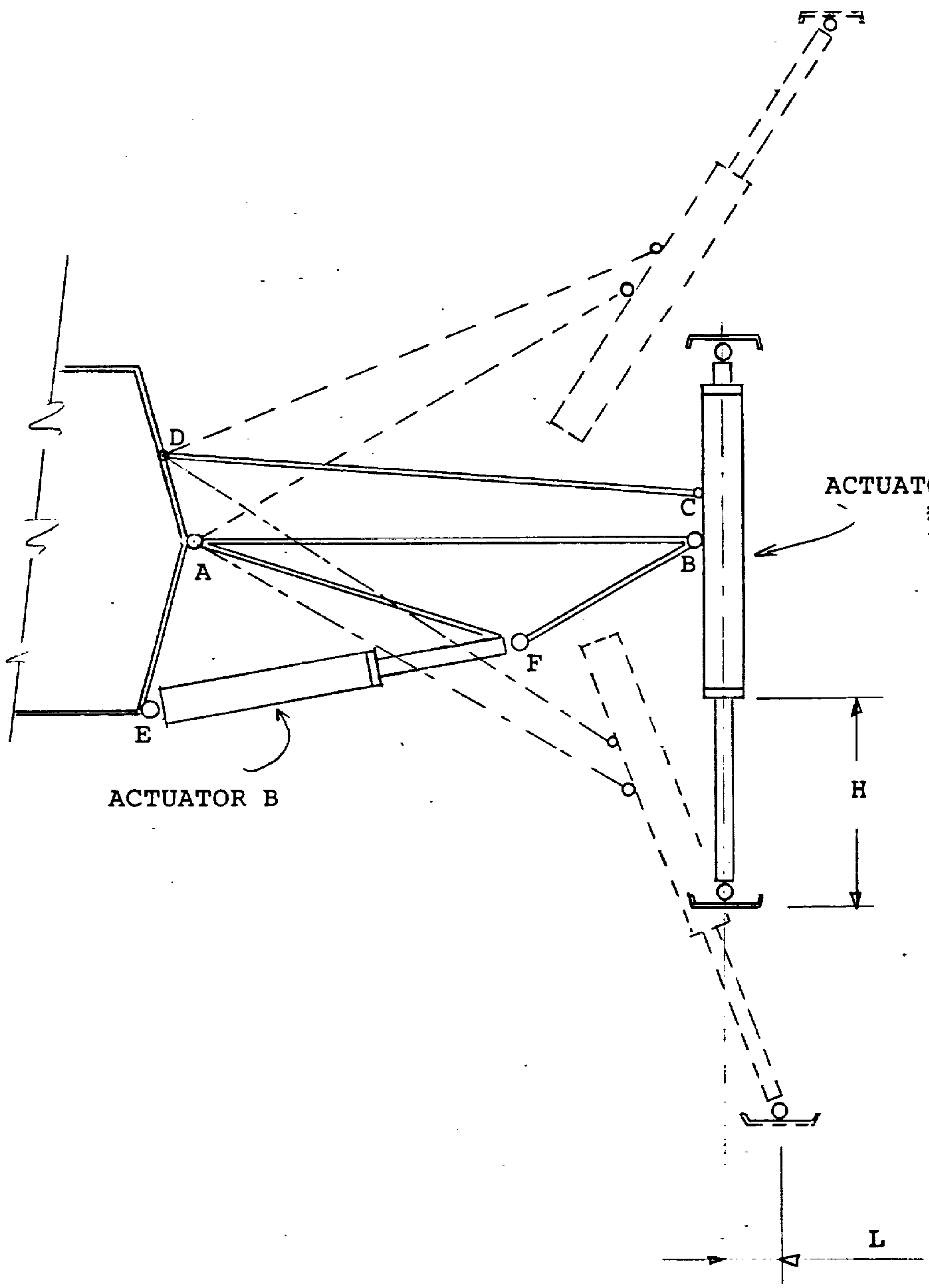


FIGURE 2D1

Alternate Actuator Design

This alternative demonstrates the principle use of rotary actuators, instead of linear actuators, in order to achieve the relative motion between the femur and the tibia.

The rotary actuator attached at the base of the femur transmits a rotary motion, via a gear box, to gear B. Gear A is attached rigidly to the tibia and both are attached to the femur at the pivot point A. The chain transfers the rotary motion of gear B to gear A with the result being angular motion of the tibia relative to the body.

This arrangement eliminates the need for a four bar linkage at the femur - tibia joint and increases the relative range of motion. The rigid construction of all memebers minimizes deformation due to torsional forces as well as bending forces.

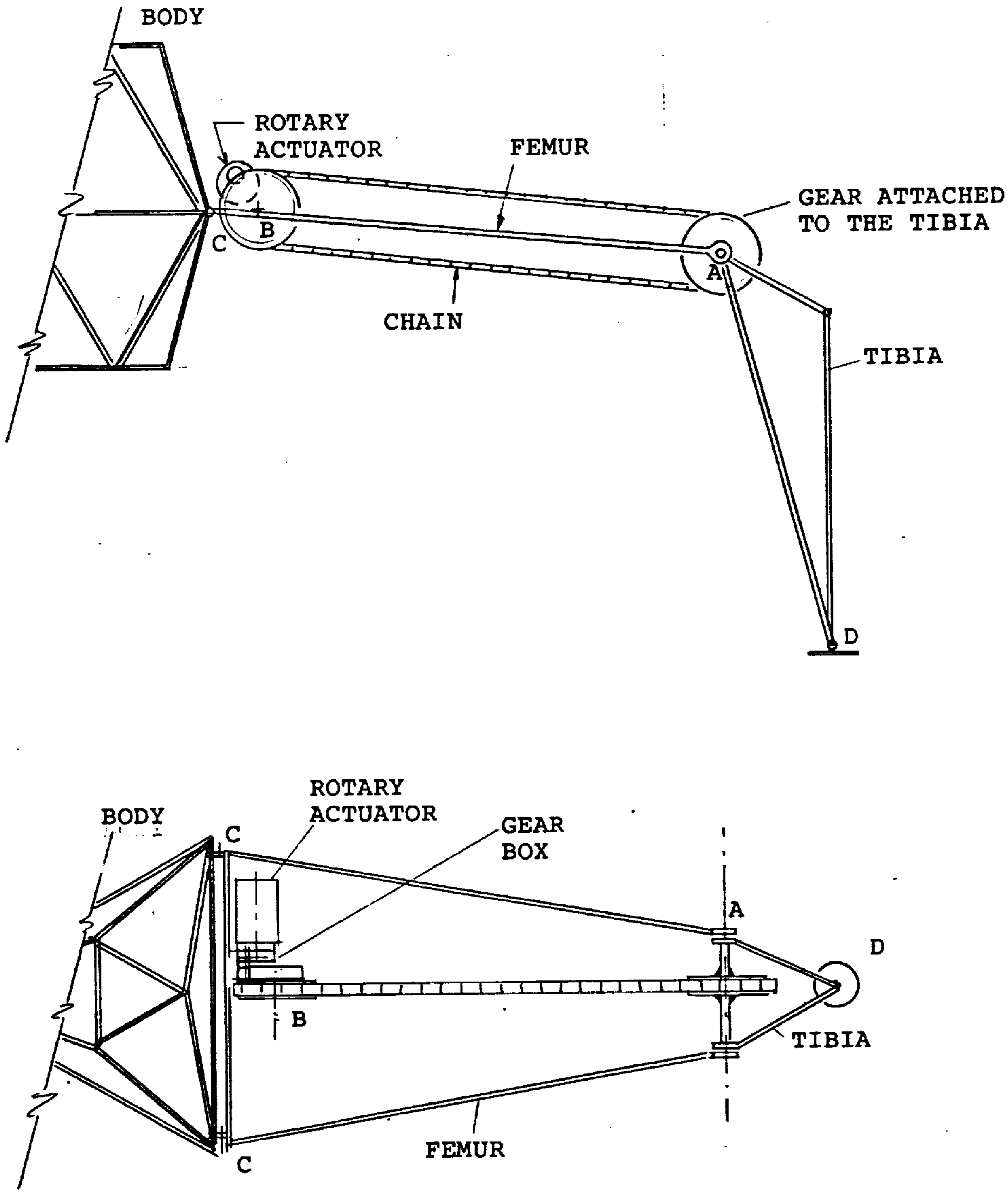

BODY
ROTARY ACTUATOR
FEMUR
GEAR ATTACHED TO THE TIBIA
B
C
A
CHAIN
TIBIA
D
BODY
ROTARY ACTUATOR
GEAR BOX
C
A
D
B
TIBIA
FEMUR
C

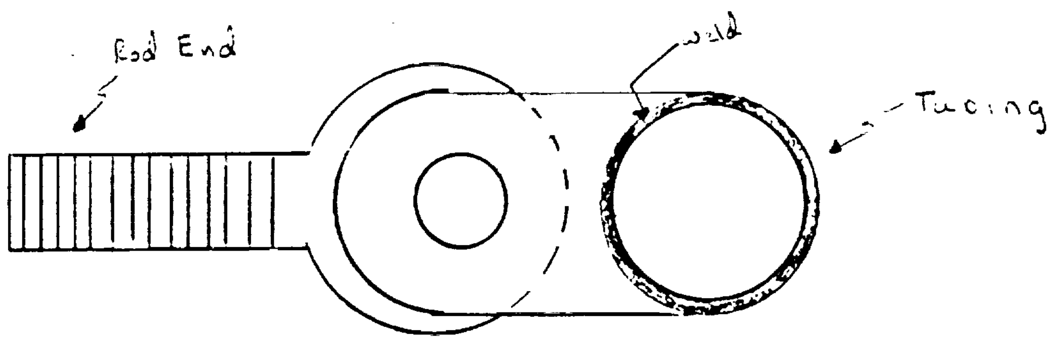
FIGURE 2D-2

Alternative Design for the Joints

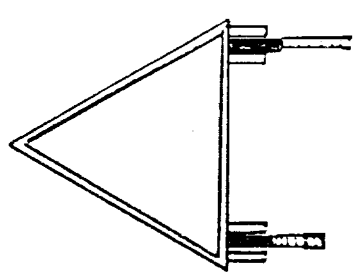
Many types of joints exist for tubular space structure design. Several include the ORBA-HUB , the MERO joint and the PG Space Structures Spherical Nodes assembly. Each is fully described and illustrated in "types of Space Trusses and Frames", by JOHN WILBUR ,pp409-412.

Alternate Design of Body Femur Connection

The bracket shown below is used to connect the femur to the body. The bracket allows the rod ends to connect to the corners of the body where the stress is the greatest. This design was dismissed because the bracket welds could not withstand the high torques created by the legs.



SIDE VIEW



TOP VIEW

ORIGINAL PAGE IS
OF POOR QUALITY

Alternative Design for Material

Several materials were analyzed for use in SKITTER II's tubular truss design. These materials included composites, steel and many different alloys. Due to cost and weight constraints, Aluminum 6061-T6 was used. Although Aluminum 5083 exhibited similiar properties and costs, the lack of literature and information made the selection of this material a gamble. Aluminum 5086 was also examined as a possible choice,however, due to its restricted source of manufacture , availability and prices were unfavorable. Composites were examined for their light weight and high strength characteristics, however, their corrosion resistance is somewhat undesirable. Composites' resistivity to corrosion could be improved with the use of an organic or anodic coating, however, the cost would then be escalated. Steel members were originally left out due to the weight criterion earlier set. At this time more research should be done analyzing steel tubing as a possible material. Due to its excellent strength characteristics steel might prove a better material on such a small design. Aluminum 6061-T6 meets all requirements and will help provide an excellent structure.

APPENDIX 3
PROGRESS REPORTS

Progress Report #1 April 14, 1988

Group #1: Tubular Space Truss Structure for Skitter II Robot

Team Members:

Richard Beecham
Linda DeJulio
Paul DeLorme
Eric Eck
Avi Levi
Joel Lowery
Joe Radack
Randy Sheffield
Scott Stevens

Organizational Meeting(3/31/88)

Discussed primary objectives of the project with Dr. Brazell. As a group, we became familiar with a previously existing model of Skitter II(Tubular Structure).

Review of Related Literature

Several books on trusses and joints(hinges) were found and are being reviewed. Literature on the existing Skitter design is also being surveyed.

Orientation on Apollo

Five members of the group are becoming familiar with the Apollo work stations in the French Building. An account was established such that a finite element program can be utilized. Twice a week, the members attend Supertab lectures given by Edward Bowden.

Group Meeting(4/11/88)

We began the meeting with a discussion of joints and hinges. Two ideas were analyzed: ball & socket joints and hinge attachments to the rods. The project was then divided up into three main segments: body, femur, and tibia. Subgroups were assigned to each part and subsequent analysis suggested.

PROGRESS REPORT #2

APRIL 21, 1988

Group #1: Tubular Space Structure for Skitter II Robot

Team Members:	Richard Beecham	Joel Lowery
	Linda DeJulio	Joe Radack
	Paul DeLorme	Randy Sheffield
	Erick Eck	Scott Stevens
	Avi Levi	

This Week's Progress:

1. We held two group meetings to divide initial research responsibilities and to advise other members of individual and sub-group progress.

2. We set up an interview time with the librarian to discuss our research needs and start our library search.

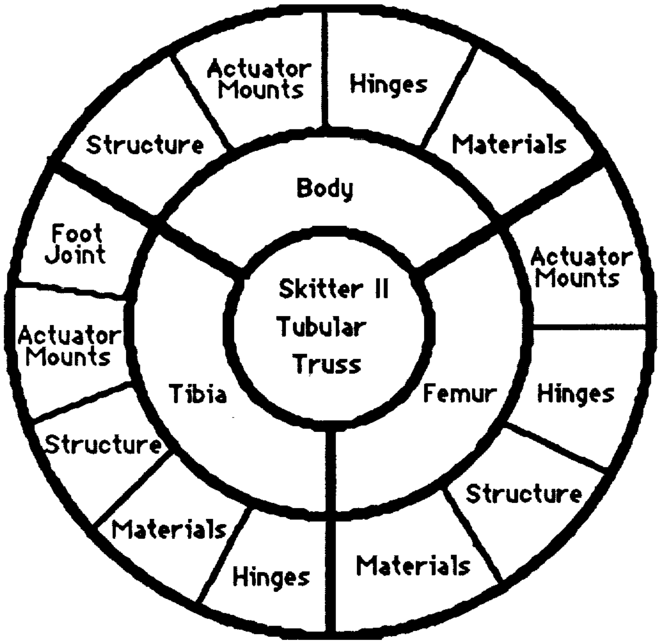
3. On-site library research on welded joints, rod-ends, and tubular structures was started using the GTEC data base and VSMF files.

4. Team members visited Yancey Bros. to look at the articulated steering device on a pan. Additionally, four-bar linkages were studied specifically for use in extending the range of motion of the Skitter legs.

5. We defined our problem statement at one of the team meetings to better focus our efforts. Additionally, we started work on a timeline to define a schedule for our project.

6. Supertab orientation is ongoing and work has been done on optimizing structures.

7. Group members have started orientation on the CADAM graphics system.


Skitter II
Tubular
Truss
Body
Femur
Tibia
Actuator
Mounts
Hinges
Materials
Structure
Actuator
Mounts
Hinges
Structure
Materials
Hinges
Materials
Structure
Actuator
Mounts
Foot
Joint

PROGRESS REPORT #3

APRIL 28,1988

Group #1: Tubular Space Structure for Skitter II Robot

Team Members:

Richard Beecham
Linda DeJulio
Paul DeLorme
Erick Eck
Avi Levi
Joel Lowery
Joe Radack
Randy Sheffield
Scott Stevens

This Week's Progress:

1. We held two group meetings. The first was primarily to review designs and to try to come up with ideas for new ones. Our second meeting was to review progress and to complete our group work.

2. We have a meeting scheduled for Friday (tomorrow) with the library research staff to discuss our research needs and get the search started.

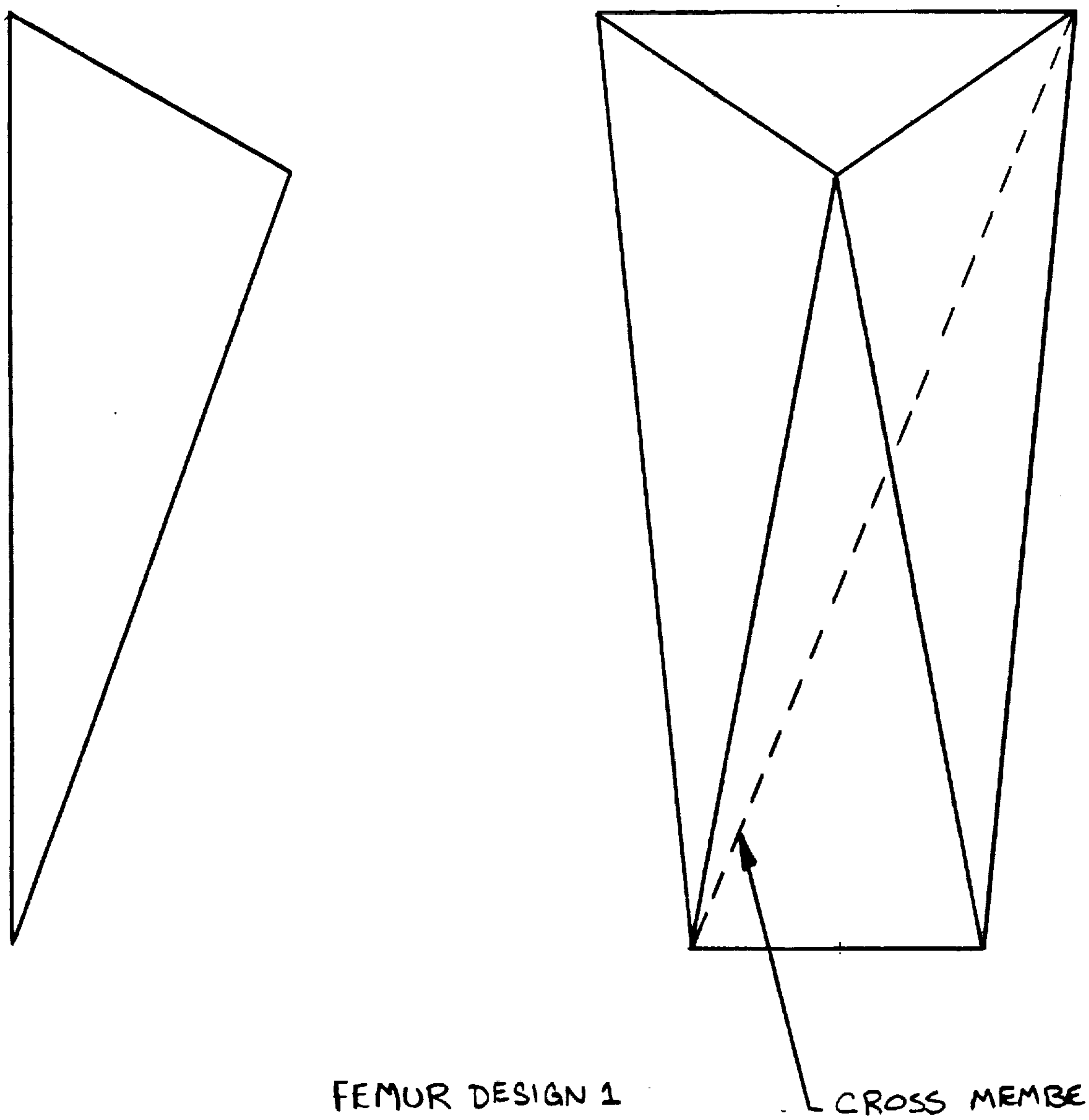
3. Supertab orientation has been completed and we now have a model of our body structure on the computer. Upon choosing the types of members we will use, analysis and optimization of the structure will begin.

4. Library research is continuing, specifically in the areas of linkages and truss structures.

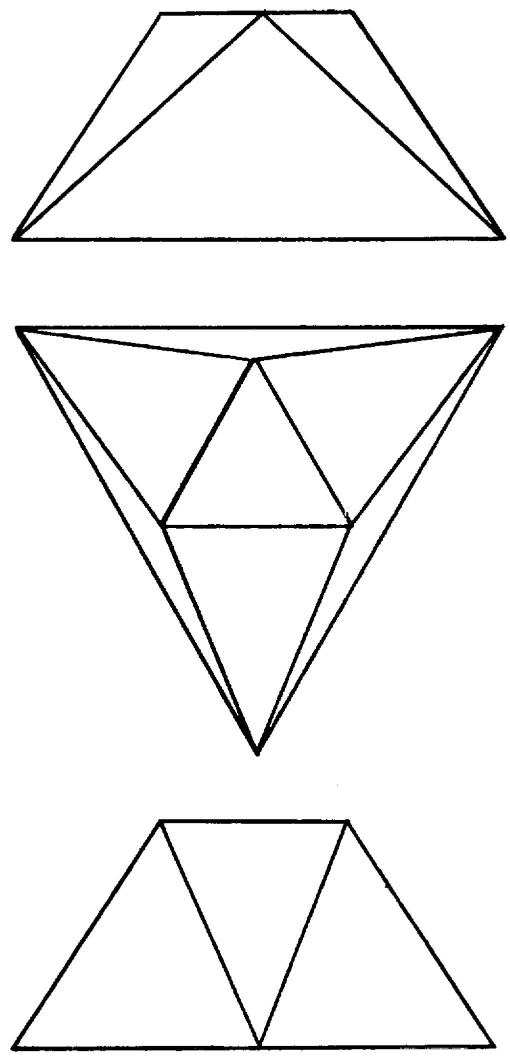
5. We have come up with several tentative designs for the legs. Additionally, design of the linkage systems is coming along.

6. We constructed several models of possible body structures and leg configurations to provide a more realistic view and to aid in our critique of them.

7. We completed our topical outline.



FEMUR DESIGN 1



BODY DESIGN

PROGRESS REPORT #4

MAY 5, 1988

Group #1: Tubular Space Structure fot Skitter II Robot

Team Members: Richard Beecham, Linda DeJulio, Paul DeLorme, Erick Eck, Avi Levi, Joel Lowery, Joe Radack, Randy Sheffield, Scott Stevens

This Week's Progress:

1. We held two group meetings. One was to review progress and discuss new designs and ideas and the other was to prepare our presentation.

2. The results of our library search will be back this week. We will review the information when it arrives.

3. Members of the team have been studying linkage designs and are close to designing one which will meet our needs.

4. Analysis is continuing on Supertab for the body structure.

5. We have a complete model of the Skitter II Robot to better view the motions of the machine and aid in our analysis.

6. Additional modeling of the body and legs is continuing and new ideas are under consideration. We have several alternative designs at this point.

7. We are working on materials selection and have consulted references in the library as well as Dr. Meyers.

PROGRESS REPORT #6 May 19, 1988

Group #1: **Tubular Space Truss Structure for Skitter II**

Group Members:

Richard Beecham
Linda DeJulio
Paul DeLorme
Eric Eck
Avi Levy
Joel Lowery
Joe Radack
Randy Sheffield
Scott Stevens

1. Monday (5/16/88): Group meeting to discuss progress and assign project segments for writing. Wednesday (5/18/88) - finalized dimensions for linkage and progress report.

2. Actuator positions decided, both for femur-body and femur-tibia attachment. Crucial link dimensions have been calculated to be used in force analysis on Supertab.

3. Four-bar linkage for femur-tibia actuator near completion. Pin connections for actuator being designed.

4. Free-body Diagrams drawn for each component(body,femur, tibia) to be used in Supertab analysis.

5. Two hinge designs near completion.

6. Material selection finalized after follow-up discussion with Dr. Carolyn Meyers. Aluminum 5083 will be recommended for final construction of Skitter II.

7. Adjustable connector for actuator body under investigation.

8. Initial drafts for abstract, body, and appendices begun.

PROGRESS REPORT #7

May 26, 1988

Group #1: Tubular Space Truss Structure for Skitter II Robot

Group Members:		
	Joel Lowery	Linda DeJulio
	Scott Stevens	Joe Radack
	Richard Beecham	Avi Levi
	Eric Eck	Paul DeLorme
	Randy Sheffield	

This Week's Progress:

1. We held two group meetings to divide the writing responsibilities and to coordinate information between group members to finalize details.

2. We completed our <u>rough</u> draft for submission and review.

3. Supertab work is progressing and nearing completion.

4. Parts drawings are being completed on the CADAM system as they are submitted by group members.

5. We are doing most of our work now on details, which include mostly dimensions, welds, and connections. These should be finalized within the next few days.

6. We are beginning now to brew the approximately 26 gallons of coffee needed for next week's all-nighters.

Record of Invention No.__________
UTC No. (if applicable)__________

GEORGIA INSTITUTE OF TECHNOLOGY

APPROVAL SHEET (Attach to DISCLOSURE OF INVENTION)

The following questions should be answered by the laboratory or school director, as applicable. The questions are designed to verify the ownership of the invention. This approval should be included when the Invention Disclosure form is submitted to the Office of Technology Transfer.

1. **Title of Invention:**

   Tubular Space Truss

2. **List of Inventor(s):**

Randv Sheffield Joel Lowery	Eric Eck Avi Leuyia
Joe Radack Scott Stevens	Richard Beachum
Linda DeJulio	Paul DeLorme

3. **Ownership:**

   In my opinion this invention:

   _XX_ A. Is owned by the Institute in accordance with the Patent Policy.

   _____ B. Was developed by the inventor(s) without use of Institute time, facilities or materials, and is not related to the inventor's area of technical responsibility to the Institute and hence belongs to the inventor(s).

4. Research project advisor approval for student submissions (if applicable):

______________________________ ______________
Advisor Date

Reviewed for Institute ownership by laboratory or school director.

______________________________ ______________
Name Date

____
Title/Unit

Record of Invention No.______
UTC No. (if applicable)______

GEORGIA INSTITUTE OF TECHNOLOGY
DISCLOSURE OF INVENTION

Submit this disclosure to the Office of Technology Transfer (OTT) or contact that office for assistance. Disclosure must contain the following items: (1) title of invention, (2) a complete statement of invention and suggested scope, (3) results demonstrating that the concept is valid, (4) variations and alternate forms of the invention, (5) a statement of the novel features of the invention and how these features distinguish your invention from the state of the art as known to you, (6) applications of the technology, and (7) supporting information.

1. Title

Technical Title: Tubular Space Truss Structure for Skitter II Robot

Layman's Title (34 characters maximum, including spaces):

Tubular Frame for Skitter II

Inventor(s): (Correspondence, patent questions, etc. will be directed to the first named inventor)

A. Signature [signature] Revenue Share%____ Date June 2, 1988

Printed Name Randy (First) (Middle) Sheffield (Last) Citizenship U.S.

Home Address 113 Northlake Drive

City Carrollton County Carroll State GA Zip Code 30117

Campus Unit/Mail Address P.O. Box 36984 Campus Phone 676-0941

B. Signature Scott William Stevens Revenue Share% ____ Date June 2, 1988

Printed Name Scott William Stevens (First Middle Last) Citizenship U.S.

Home Address 607 Trailwood Lane

City Marietta County Cobb State GA Zip Code 30064

Campus Unit/Mail Address P.O. Box 30386 Campus Phone 676-0582

C. Signature Joel Keith Lowery Revenue Share%____ Date June 2, 1988

Printed Name Joel (First) Keith (Middle) Lowery (Last) Citizenship U.S.

Home Address 1028 The Falls Parkway

City Duluth County Gwinnett State GA Zip Code 30136

Campus Unit/Mail Address P.O. Box 35102 Campus Phone 497-0436

9/87

Record of Invention No.______
UTC No. (if applicable)______

DISCLOSURE OF INVENTION

2. Statement of Invention:

Give a complete description of the invention. If necessary, use additional pages, drawings, diagrams, etc. Description may be by reference to a separate document (copy of a report, a preprint, grant application, or the like) attached hereto. If so, identify the document positively. The description should include the best mode that you presently contemplate for making (the apparatus or material invented) or for carrying out the process invented.

SKITTER II is a three legged transport vehicle designed to demonstrate the principle of a tripod walker in a multitude of environments. The design is based on few moving parts and a simple mechanical system. The motivation behind these systems is that a few moving parts and a simple mechanical system will increase reliability and decrease maintenance.

The design calls for an efficient structure which consists of as few members as possible. The main goals behind the design of the SKITTER II is to improve the strength, mobility, flexibility, reliability, and the range of motion while keeping the total weight to a minimum.

The structural design consists of four major parts; the central body and the legs. The legs are connected to the central body in 120° intervals. Each leg is made up of two parts; a femur and a tibia. The relative motion between the femur and tibia is controlled by electromechanical actuators. 1 inch and 3/4 inch tubular aluminum members are utilized throughout the entire structure.

Inventor(s)	Randy Sheffield	June 2, 1988
	Joel Lowery	June 2, 1988
	Joe Radack	June 2, 1988
	Scott Stevens	June 2, 1988
	Linda DeJulio	Date June 2, 1988
	Eric Eck	June 2, 1988
	Avi Leuyia	Date June 2, 1988
	Richard Beachum	June 2, 1988
	Paul DeLorme	Date June 2, 1988
Witness*	Gary McMullen	Date 6/2/88
	Dwight N. Blair	Date 6/2/88

*The witness should be technically competent and understand the invention.

DISCLOSURE OF INVENTION

3. Results Demonstrating the Concept is Valid:

Cite specific results to date. Indicate whether you have completed preliminary research, laboratory model, or prototype testing.

Preliminary research on Structural Design Research Corporations Ideas 3.8A Super Tab finite element analysis has been completed verifying that the structure will not fail under the specified loading conditions. The laboratory model shows the body-femur and femur-tibia linkages will yield ranges of motion of 100 degrees and 180 degrees respectively.

4. Variations and Alternative Forms of the Invention:

State all of the alternate forms envisioned to be within the full scope of the invention. List all potential applications and forms of the invention, whether currently proven or not. (For example, chemical inventions should consider all derivatives, analogues, etc.) Be speculative in answering this section. Indicate what testing, if any, you have conducted on these alternate forms.

A Skitter utilizing linear actuators for the tibia instead of a tubular frame.

There has been no testing on this alternative.

Inventor(s)	Randy Sheffield	June 2, 1988
	Joel Lowery	June 2, 1988
	Joe Radack	June 2, 1988
	Scott Stevens	June 2, 1988
	Linda DeJulio	Date June 2, 1988
	Eric Eck	June 2, 1988
	Avi Leuyia	Date June 2, 1988
	Richard Beachum	June 2, 1988
	Paul DeLorme	Date June 2, 1988

Witness* Gary McMurray (printed name) Date 6/2/88

Dwight N. Blair (printed name) Date 6/2/88

Record of Invention No.______
UTC No. (if applicable)______

DISCLOSURE OF INVENTION

5. Novel Features:

a. Specify the novel features of your invention. How does the invention differ from present technology?

The femur-tibia range of motion is 180 degrees. The structure moves by two linear actuators per leg whereas the existing model currently uses four actuators per leg.

b. What deficiencies or limitations in the present technology does your invention overcome?

The Skitter II will be able to walk upside down and be able to right itself.

c. Have you or an associate searched the scientific literature with respect to this invention? Yes______No__X__. Have you done a patent search? Yes______No__x__. If yes in either case, or both, indicate what pertinent information you found and enclose copies if available. Also indicate any other art you are aware of (whatever the source of your information) that is pertinent to your invention. Enclose copies of descriptions if available. (Note: An inventor is under duty by law to disclose to the U.S. Patent and Trademark Office any prior art known to him or her.)

Inventor(s)	Randy Sheffield	June 2, 1988
	Joel Lowerv	June 2, 1988
	Joe Radack	June 2, 1988
	Scott Stevens	June 2, 1988
	Linda DeJulio	Date June 2, 1988
	Eric Eck	June 2, 1988
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	Richard Beachum	June 2, 1988
	Paul DeLorme	Date June 2, 1988

Witness Gary McMurray (printed name) Date 6/2/88

Dwight N. Blair (printed name) Date 6/2/88

Record of Invention No.________
UTC No. (if applicable)________

DISCLOSURE OF INVENTION

6. Application of the Technology:

List all products you envision resulting from this invention. For each, indicate whether the product could be developed in the near term (less than 2 years) or would require long-term development (more than 2 years).

Lunar vehicle for NASA (near term).

Hazardous Terrain Earth Vehicle (near term).

Inventor(s)	Randy Sheffield	June 2, 1988
	Joel Lowery	June 2, 1988
	Joe Radack	June 2, 1988
	Scott Stevens	June 2, 1988
	Linda DeJulio	Date June 2, 1988
	Eric Eck	June 2, 1988
	Avi Leuyia	Date June 2, 1988
	Richard Beachum	June 2, 1988
	Paul DeLorme	Date June 2, 1988

Witness Gary McMurray Date 6/2/88
(printed name)
Dwight W. Blair Date 6/2/88
(printed name)

Record of Invention No.________
UTC No. (if applicable)________

DISCLOSURE OF INVENTION
SUPPORTING INFORMATION

1. Are there publications such as theses, reports, preprints, reprints, etc. pertaining to the invention? Please list with publication dates. Include manuscripts (submitted or not), news releases, feature articles and items from internal publications. Supply copies if possible.

2. On what date was the invention first conceived? 3-31-88 Is this date documented? yes Where? Georgia Institute of Technology Are laboratory records and data available? Give reference numbers and physical location, but do not enclose.

   No.

3. Give date, place, and circumstances of any disclosure. If disclosed to specific individuals, give names and dates.

   N/A

4. Was the work that led to the invention sponsored by an entity external to Georgia Institute of Technology? Yes X No____

   a) If yes, has sponsor been notified? Yes X No____

   b) Sponsor Names: GIT Project Nos.

   NASA

5. What firms do you think may be interested, in the invention and why. Name specific persons within the companies if possible.

   NASA - NASA has a need for a lunar based low maintenance vehicle.

DISCLOSURE OF INVENTION
SUPPORTING INFORMATION

6. Setting aside your personal interest, what do you see as the greatest obstacles to the adoption of your invention?

Manufacturing the tubular structure will be the biggest obstacle due to the complexity of the tubing welds.

7. Alternate Technology and Competition:

a. Describe alternate technologies of which you are aware that accomplish the purpose of the invention.

Know of no other existing technology.

b. List the companies and their products currently on the market which make use of these alternate technologies.

N/A

c. List any research groups currently engaged in research and development in this area.

University of Houston. School of Mechanical Engineering

8. Future Research Plans:

a. What additional research is needed to complete development and testing of the invention? What time frame and estimated budget is needed for the completion of each step?

Additional research is needed on tubular frame optimation (10 weeks, $0.00).

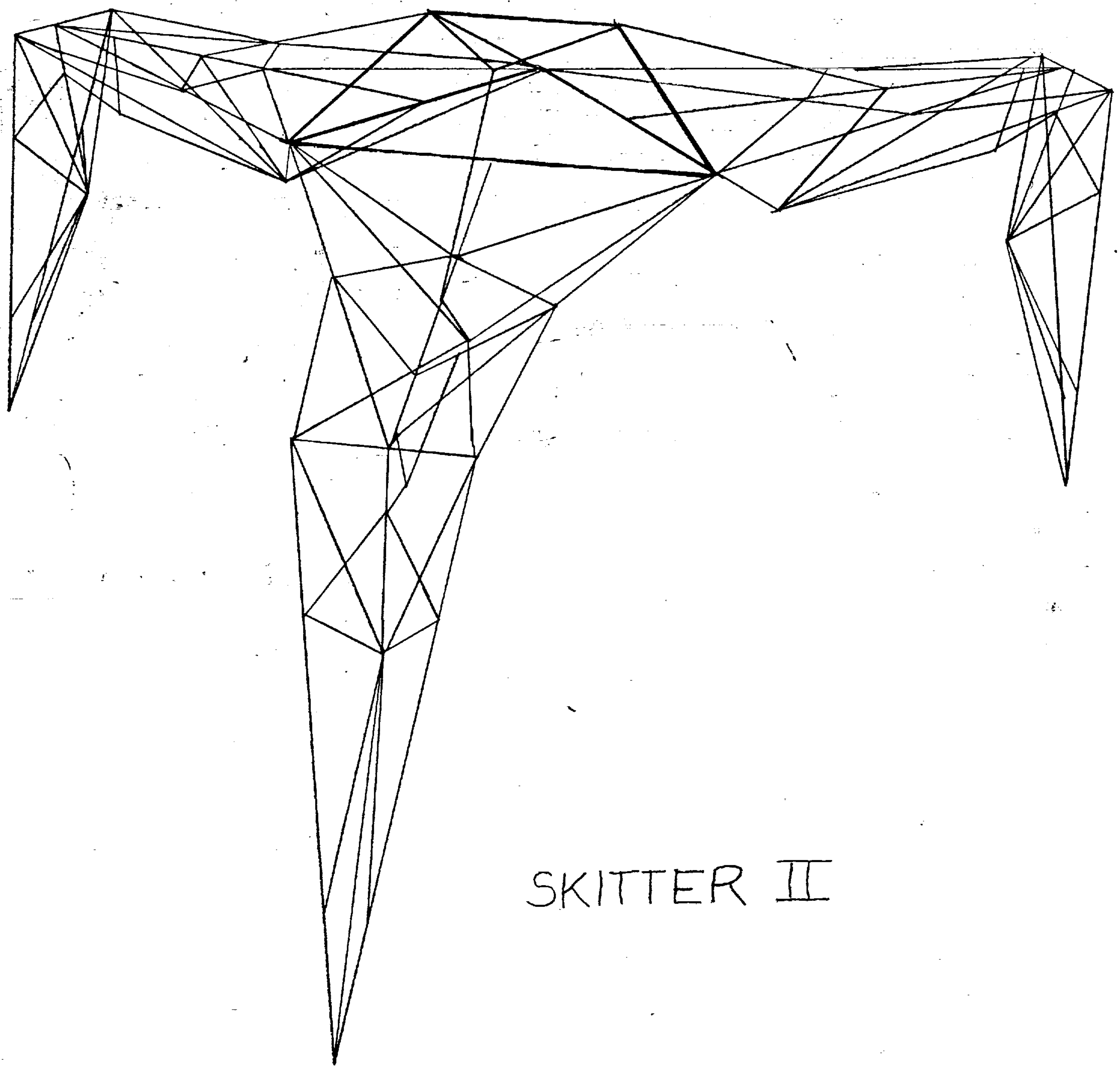
b. Is this additional research presently being undertaken? Yes___No_X_

c. If yes, under whose sponsorship?

d. If no, should corporate sponsorship be pursued? Yes_X__No_____

Suggested corporation(s)____NASA____

9. Attach, sign and date additional sheets if necessary. Enclose sketches, drawings, photographs and other materials that help illustrate the description. (Rough artwork, flow sheets, Polaroid photographs and penciled graphs are satisfactory as long as they tell a clear and understandable story.)



SKITTER II